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Contents

Mutual Interference Of Bridge Piers Placed In Staggered Arrangement On Scour Depth

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ABSTRACT

The work reported herein is concerned with a carefully controlled extensiveexperimental scour around a group of bridge piers placed in staggered arrangement in uniform sediment at varied pier spacing under steady uniform flow clear water scour conditions at flow intensity equal to 0.95.The objective of present study is to investigate the effect of mutual interference of bridge piers placed in staggered arrangement on the scour depth.To accomplish the taska series of experiments was conducted wherein three circular pier models of same diameter were used. Two of the three pier models were set on upstream across the flume at right angles to the flow direction at fixed centre to centre lateral spacing between the piers. The third pier model was located on downstream along the bisector of the upstream pier models at varied clear long itudinal pier spacing The lateral centre to centre pier spacing was so set that the scour depths at two upstream piers were free from the effect of lateral mutual interference and only the interference of the downstream pier remains to affect the scour depth at piers. The experimental data on variation of scour depth are collected, processed and analyzed to interpret the results. Present study reveals that the piers placed in staggered arrangement at close proximity have considerable mutual interference effect on scour depth which may lead to bridge failure, if pier group effect is ignored and bridge piers are designed merely as an isolated pier.Themaximum effect of mutual interference is found at relative pier spacing of 10.

Key elements: Local scour, b ridge pier, pier spacing, scour hole, experimental

1. INTRODUCTION

Scour is the process of lowering of river-bed around an obstruction due to removal of the bed material by erosive action of flowing water. In case of local scour the lowering of the riverbed occurs in the vicinity of the structure. In spite of significant amount of research on single pier scour, failure of many bridges has rekindled interest in furthering understanding of the pier group scour.

1.1 Local scour at group of bridge piers

In case of scour around group of piers, the presence of piers can generate a complex interaction in the hydrodynamic characteristics of the flow field near the piers themselves and therefore, lead to the occurrence and development of a scour process that is quite different from one which occurs around a single pier.

Local scour around a single bridge pier is affected by a large number of inter-dependant variables. The flow, sediment, pier characteristics and time are the main variables affecting this phenomenon. As a consequence of extensive research by several investigators on the phenomenon of local scour around a single bridge pier, a large number of designrelationships have been bequeathed to the bridge designer. Notwithstanding this, many bridges still suffer damage by local scour. This is due to more intense complexities due to the mutual interaction of piers group. It indicates that in addition to the variables affecting local scour around a single pier, spacing of piers and pattern of piers' placement in the riverbed also affect the scour depth and scour hole characteristics around group of piers. One of the patterns of piers placement may have staggeed arrangement (Figure 1). Timonoff (1929), Garde. (1961), Basak *et. al.*(1975), Hannah (1978), Elliot, K.R. and Baker, C.J. (1985), El-Taher, R.M. (1984, 85), Shah (1988), Kothyari, U.C., (1989), Breusers and Raudkivi (1991), Garde, *et. al* (1995), Vittal *et. al.*(1994), Babaeyan-Koopaei and Valentine (1999) and Mubeen Beg (2008) have made some studies on scour around group of piers.

Hannah (1978) carried out detailed investigation on local scour at groups of cylindrical piles with steady and uniform flow and clear-water condition. The mechanisms involved in the scouring process at piers group placed in tandem arrangementwere identical as reinforcing, sheltering, vortex shedding.

1.1.1 Reinforcing

It causes increased scour depths at the front pier. Bed material is continuously lifted from the base of the hole by the flow, which is not, however, capable of removing this material from the scour hole. When the downstream pier is so placed that the scour holes overlap, the bed level is lowered at the rear of the upstream scour hole. It is, thus, easier for the flow to remove material from this hole and it deepens. As the pier separation increases, the reinforcing effect decreases gradually and disappears when the maximum bed level between the piers returns to the undisturbed bed level.

1.1.2Sheltering

The presence of an upstream pier can cause a reduction in effective approach velocity for downstream pier. This reduction weakens the effect of horseshoe vortex and thereby reduces scour at the downstream pier. A second form of sheltering occurs if the material scoured from the upstream pier is deposited on the bed in front of the downstream pier. Flow is then deflected up from the bed near the downstream pier, which reduces the horseshoe vortex strength. As pier separation increases, thevelocity deficit in the wake of the upstream pier disappears and the sheltering effect decreases. All the studies of scouraround pier groups substantiate the existence of sheltering mechanism for small angles of attack.

1.1.3Vortex shedding

Vortices shed from an upstream pier are convected downstream. When a second pier is so placed close to one of the vortex shedding paths, the vortices assist in lifting the material from the scour hole. The scouring potential of the shed vortex is a function of its convection speed and of the distance between the path and the affected pier. This effect, therefore, decreases more rapidly for piers in line with the flow than for those at angles of attack which place downstream piers on the paths traced by vortices shed by upstream pier.

1.1.4Horseshoe vortex compression

When piles are placed transverse to the flow, each will have, except at very close spacing, its own horseshoe vortex. As pile spacing is decreased, the inner arms of the horseshoe vortices will be compressed. This causes velocities within the arms to increase with a consequent increase in scour depths. This compression also exists for piles in staggered arrangement.

2. EXPERIMENTAL PROGRAMME

Experiments were conducted in the Department of Civil Engineering, Z.H. College of Engineering and Technology, AMU, Aligarh, U.P., India. 33 mm galvanized steel circular cylindrical piers were used in present study. As shown in figure 1, two of the three pier models were set on upstream across the flume at right angles to the flow direction at a fixed centre to centre lateral spacing between the piers Z_c/b, where Z_c is the center to center lateral spacing between the upstream piers and b is the diameter of the pier model. The third pier model was located on downstream along the bisector of the upstream pier models at varied clear longitudinal pier spacing X_c/b= 5, 10, 15, 20, 25, 30, 35, 40, 50, 60, 70, 80 and 90, where x is the center to center distance between the upstream and downstream pier models along the length of the flume and b is the diameter of the pier model. The lateral centre to centre pier spacing Z_c/b was set at 9 because at this lateral pier spacing, the scour holes at piers are found to be free from the effect of lateral mutual interference and only the interference of the downstream pier remains to affect the scour depth at upstream piers.

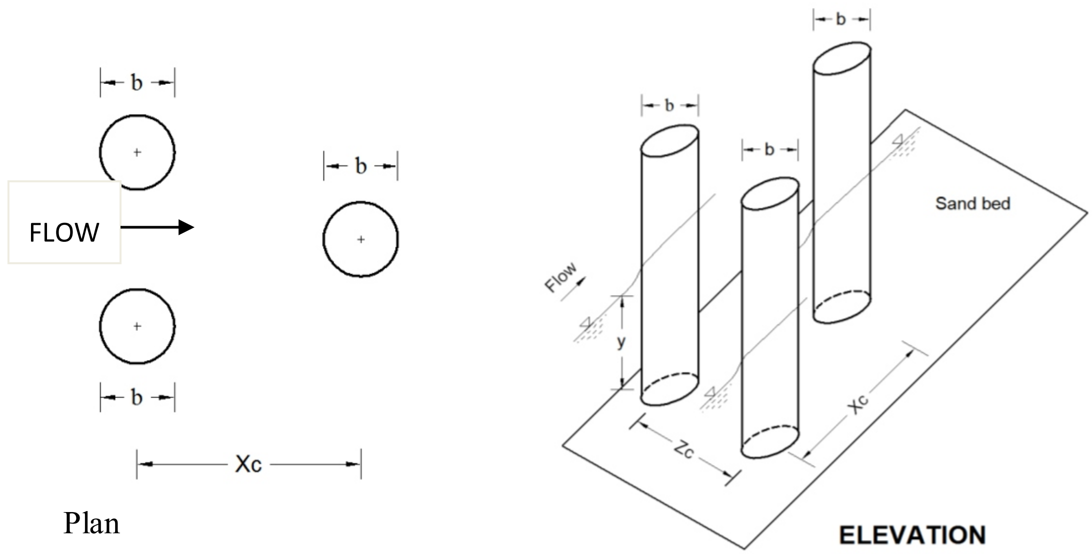


Figure- 1. Piers of same size in placed in staggered arrangement

Tables 1 and 2 give the flow, sediment and pier parameters used in experiments.

Table 1 Properties of sediment and piers used in present study.

$D_{84.1}$ (Mm)	$D_{15.9}$ (Mm)	D_{50} (Mm)	Geo.- standard dev. $_G$(mm)	Specific GravityS_s	Pier size used Circular Piers	Angle Of Repose	U/U_C
1.03	0.73	0.95	1.187	2.65	33mm	32°	0.95

Table 2. Computed mean flow parameters.

Discharge (m^3/s)	Depth Of Flow y_0 (mm)	Mean Velocity U (m/s)	Threshold Velocity U(m/s)	Froude No. F_{f_r}	Critical Froude No. F_{rc}	Average energy slope S_0
0.04141	140.0	0.391	0.4127	0.3328	0.35028	0.001

Since in present study clear-water experiments were conducted using coarse sediment of 0.95 mm median diameter, duration of 10 hours was considered adequate.

To form a basis for analyzing results on group of piers placed in staggered arrangement, a series of experiments on 33 mm diameter single pier was also performed.

Each experiment commenced from a condition of still water at the predetermined flow depth over a leveled bed surface. The time of start of initial movement of sediment, and of water surface establishment were recorded. On the completion of the experimental run, the water supply to the flume was gradually stopped and the water from the flume was drained off carefully so that the scour holes and the scour patterns around the piers developed by the flow were not disturbed.

3. DATA COLLECTION

Detailed experimental data during the experimental runs and after experimental runs were collected The dynamic scour depths at the nose of piers were measured and recorded during the entire experimental runs at suitable interval of time. However, as each experimental run was over, scoured area around the piers was surveyed with point gauge and detailed static scour measurements were made and recorded. The length of scour holes at front and rear faces of upstream and downstream piers, width of scour holes at front faces of upstream and downstream piers, the areal extent of scour around the piers and the length of sediment deposition on rear face of upstream and downstream piers were measured and recorded. Photographs of scour holes and areal extent of scour were taken as shown in figure 2.

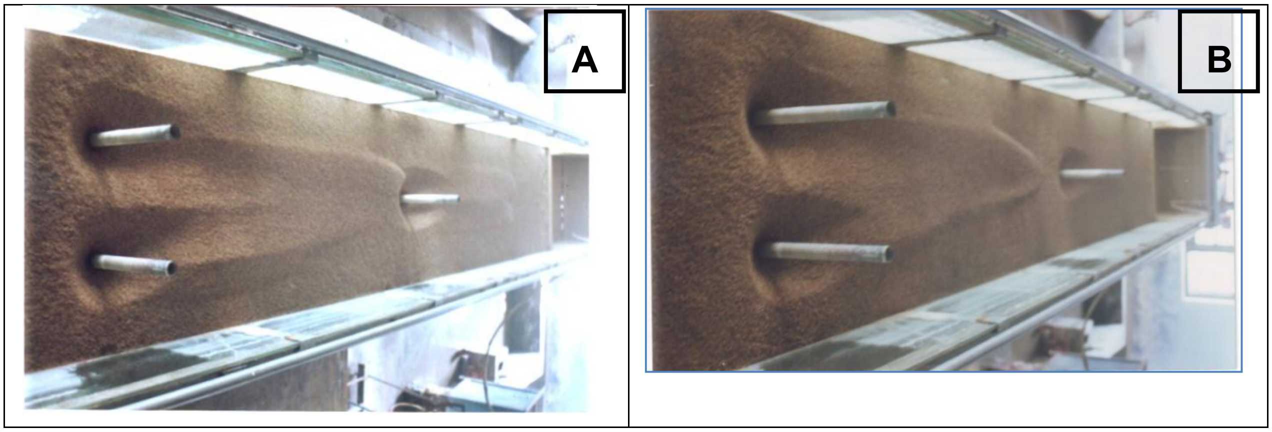


Figure 2. Scour and deposition patterns around piers placed in staggered arrangement at varied pier spacing (A) X_c/b=50 (B) X_c/b=60

4. RESULTS AND DISCUSSION

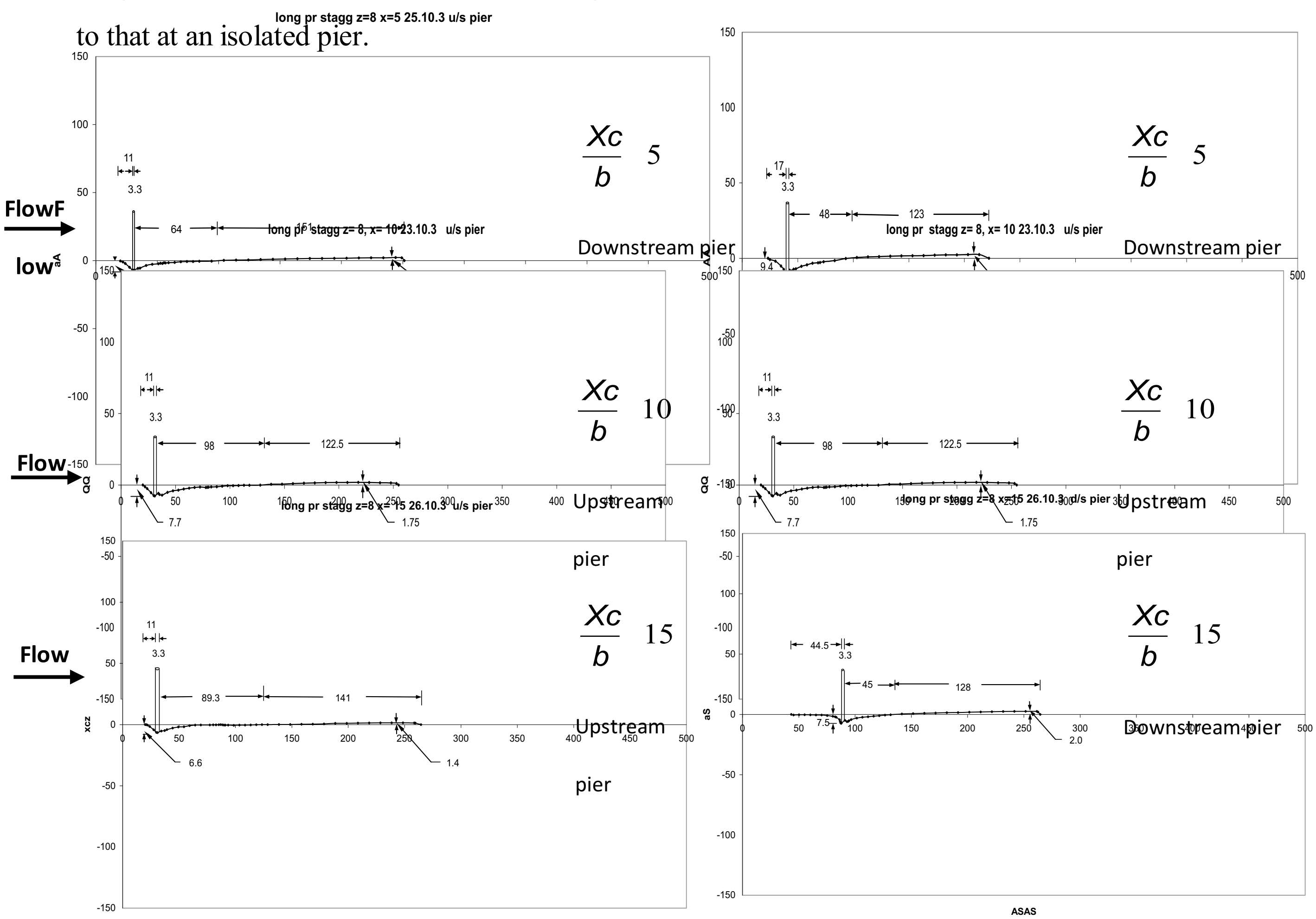
The data on various characteristics of scour holes collected during and after the experimental runs are then processed and analyzed as under.

In order to analyze the results obtained from present experiments for the case of local scour at three piers placed in staggered arrangement, the longitudinal scour profiles, lateral profile of scour hole and areal extents of scour are plotted against relative pier spacing *'x/b'*. Some distinctive cases of areal extent of scour and longitudinal profile of scour are considered herein for analysis and discussion. In order to analyze the results on scour around staggered piers, photographs showing scour and deposition patterns developed around the piers were taken at the end of each experiment. Photographs for some typical pier cases are shown in Fig2.

As the objective of this part of present study is to investigate the effect of longitudinal spacing between upstream and downstream piers placed in staggered arrangement on bridge pier local scour, the transverse pier spacing between the upstream piers is kept same at Z_c/b=9 since at this transverse pier spacing the effect of compression of horseshoe vortices between the two transverse piers is negligible as found in present study (Section 5.6 of this chapter) and also reported by Hannah (1978). The analysis of results achieved from experiments in this part of present study is carried out under the following heads:

4.1 Variation of scour depth along flume length

In order to analyze the results obtained from present experiments on staggered piers arrangement, the scour depths at upstream and downstream piers along flume length in flow direction are plotted for varied longitudinal pier spacing *'X_c/b'* and some critical cases are shown in Fig. 3. The depth of local scour, length of the scour holes at the upstream and downstream faces of piers and length of sediment deposition at the downstream face of piers, are illustrated in these longitudinal scour profiles. It can be seen that at short pier spacing *'X_c/b'*, the rate of scouring at downstream pier remains higher than the upstream ones owing to the increased scour intensity caused by the approachment of flow from two upstream piers at an angle of attack *'α'* up-to 45°. However, as the pier spacing *'X_c/b'* increases to 90, the total angle of attack of two upstream piers falls below 7.5 at whichthe effectof angle of attach at downstream pier becomes insignificant. As a result, the rate of scouring at upstream and downstream piers becomes identical to that at an isolated pier.



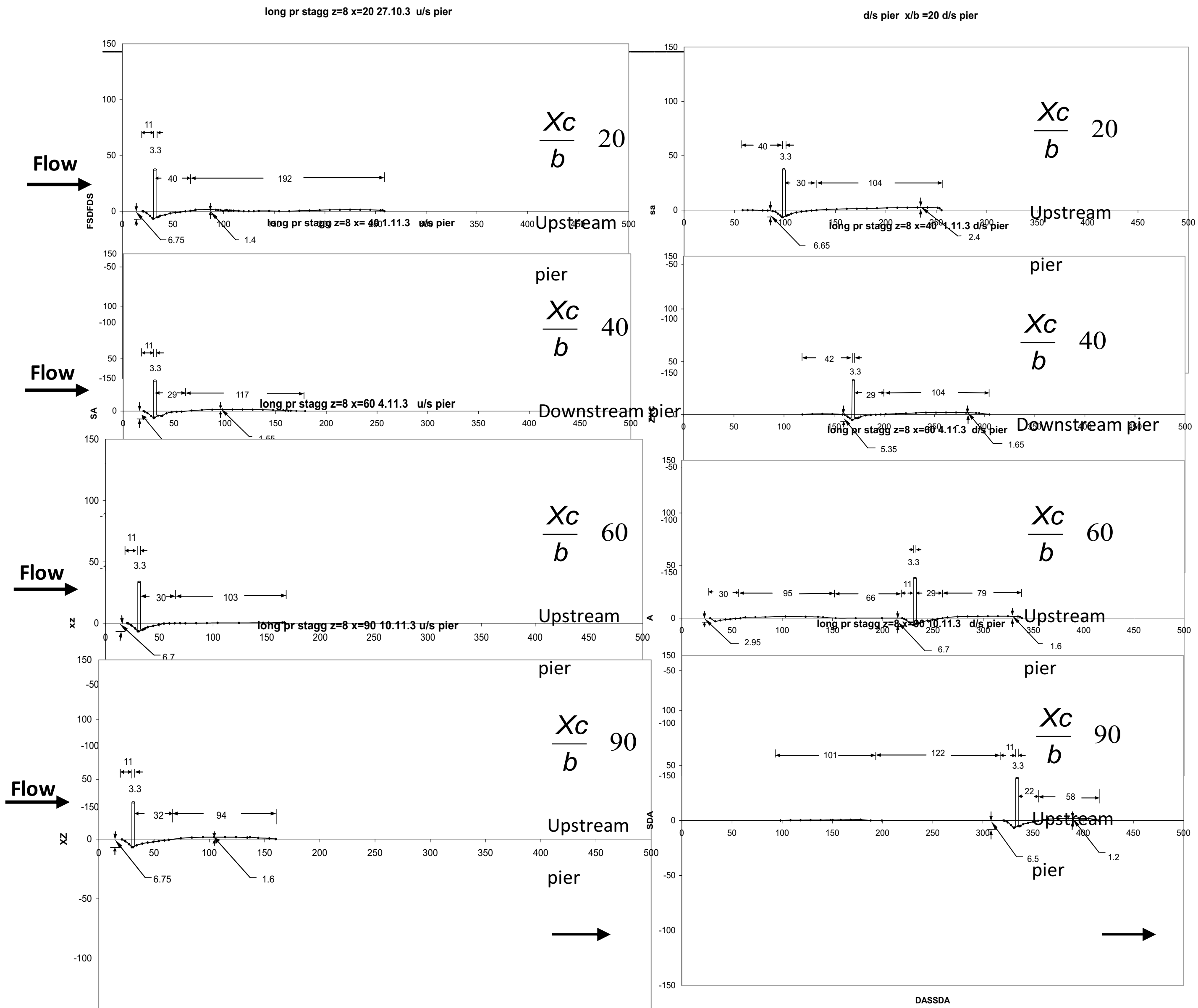


Fig. 3. Longitudinal profiles for three piers of same size in staggered arrangement for varied pier spacing Xc/b.

4.2 Scour depth variation at upstream and downstream piers

The relative scour depths measured at upstream piers '$d_{st(u)}/ds_{(i)}$' and downstream pier '$d_{st(d)}/ds_{(i)}$' are plotted against the relative pier spacing 'X_c/b' as shown in Fig.4. It is observed that the scour depth at upstream and downstream piers initially increases with pier spacing and reaches to a maximum at pier spacing X_c/b=10. The reason for this maxima in scour depth at the downstream pier at $X_c/b=10$, can be attributed to the approaching flow, which after interacting with the two upstream piers, approaches to the downstream pier at such an angle of attack at which the strength of horseshoe vortex at downstream pier is highly enhanced. The arrangement of two upstream piers at lateral pier spacing Z_c/b = 9 and downstream pier at longitudinal pier spacing X_c/b = 10 produces an angle of attack of 22.25º each with the two upstream piers. As a result, the total effective angle of attack equals to 45º which has been found to be the most critical angle of attack producing severe effect on scour depth (Hannah, 1978).

At pier spacing X_c/b>10, the scour depth at the downstream pier decreases with increasing pier spacing and reaches to a minimum at X_c/b=40. Thereafter, it increases upto pier spacing X_c/b=65 and then remains invariable upto X_c/b=90. The decrease in scour depth at the downstream pier at 10<X_c/b≤40, is attributed to the sheltering of downstream pier by the wakes of upstream piers due to which the velocity of flow approaching towards downstream pier decreases.

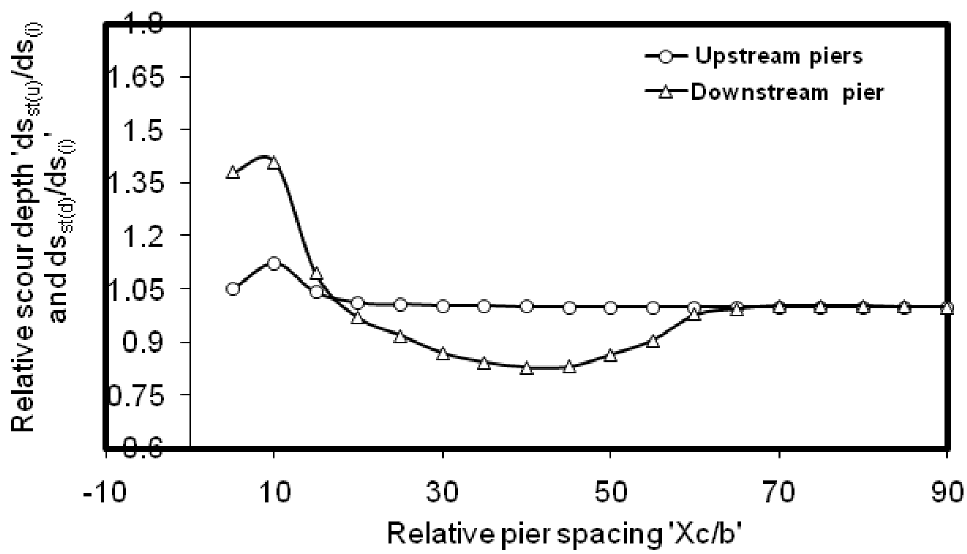


Fig. 4 Variation of relative scour depth at upstream and downstream piers placed in staggered arrangement '$d_{st(u)}/ds_{(i)}$' and '$ds_{st(d)}/ds_{(i)}$' with pier spacing X_c/b (where $ds_{st(u)}$= scour depth at upstream piers, $ds_{st(d)}/ds$ =scour depth at downstream pier and $ds_{(i)}$= scour depth at isolated pier)

Also, at these pier spacings, the total effective angle of attack produced by the upstream piers remains ≤ 30º which causes less effect on the scour depth as investigated by Hanna (1978). The increasing trend in scour depth at downstream pier at 40<X_c/b≤65 indicates an increase in the velocity of flow approaching towards downstream pier due to the reduction in the sheltering effect of wakes of upstream piers. At X_c/b≥65, the downstream pier goes out of the wake region of upstream piers as a result of which the velocity of flow approaching to the downstream pier regains its original value and the scour depth remains fairly constant and is same as that of an isolated pier upto pier spacing X_c/b=90. Another reason for the scour depth being constant can be attributed to the total effective angle of attack produced by the upstream and downstream piers at longitudinal pier spacing 65<X_c/b≤90 being less than 7.5º which has an insignificant effect on the scour depth as established by Hannah (1978).

The increase in scour depth at the upstream piers in the range 5<X_c/b≤10, is attributed to the reinforcing effect caused by the downstream pier, which remains dominant as evident from Fig. 5.84 upto X_c/b=20. Beyond this spacing, the reinforcing effect at upstream piers disappears almost completely and the scour depth becomes constant for pier spacing 20<X_c/b<90.

4.3 Scour depth variation between upstream and downstream piers

Fig.5 shows variation of bed level (*i.e.*, maximum scour depth) between upstream and downstream piers. It is observed that the bed level between the upstream and downstream piers decreases upto X_c/b=30, remains constant between pier spacing X_c/b= 30 to 60 and increases thereafter upto X_c/b=90.

The decrease in bed level up-to X_c/b=30, is attributed to the shielding effect of wakes developed at the downstream end of the piers placed at the upstream.

Bed level remains constant between X_c/b=30 to 60 due to the balance maintained between effects of shed vortices of upstream piers and shielding of wakes of upstream piers by downstream pier..

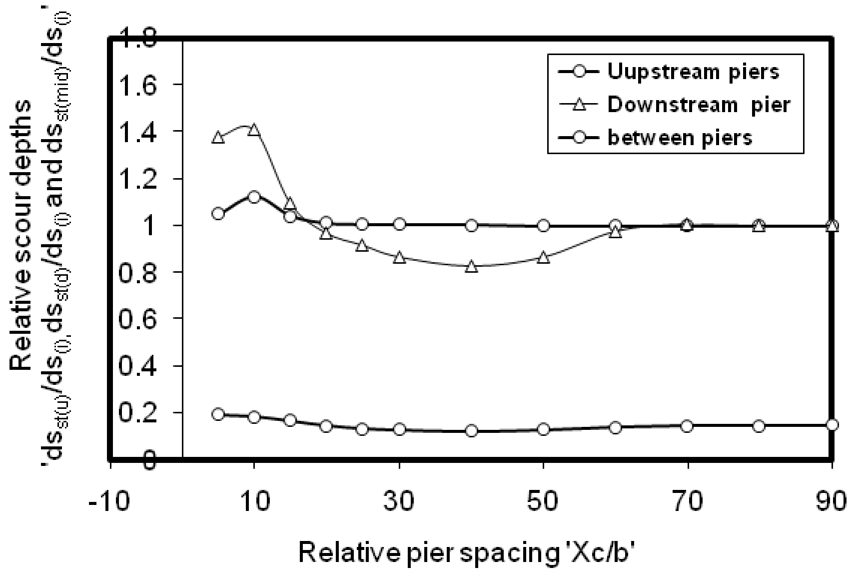


Fig.5 Variation of relative maximum scour depth at midway between upstream and downstream piers placed in staggered arrangement '$d_{st(mid)}/ds_{(i)}$' with pier spacing 'X_c/b' (where $d_{st(mid)}$= scour depth at midway between the piers, $ds_{(i)}$ = scour depth at isolated pier).

The increase in bed level between X_c/b= 60 and 90 is ascribed to a decrease in the shielding effect of wakes of upstream piers.

4.4 Scour depth variation at downstream pier with respect to upstream piers scour depth

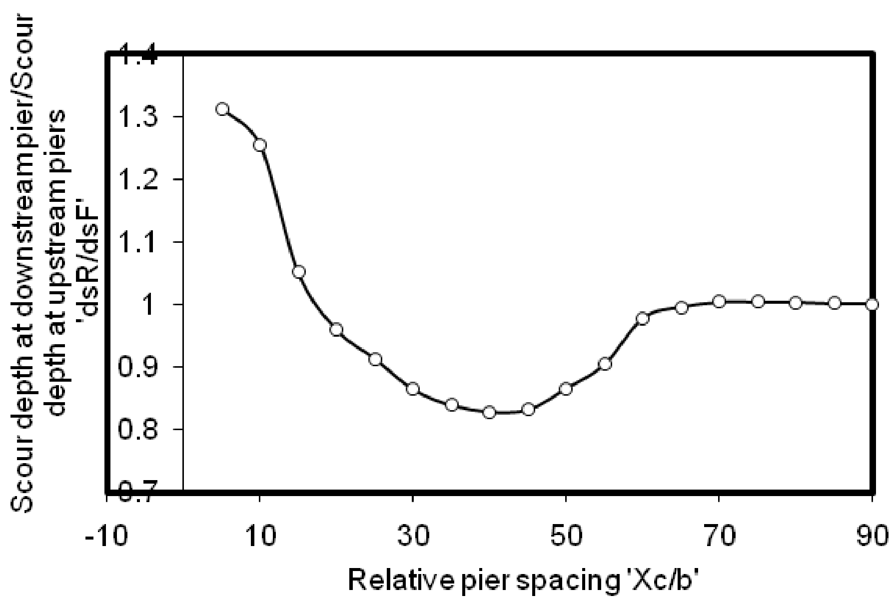


Fig. 6 Variation of relative scour depth at downstream pier with respect to that of upstream piers placed in staggered arrangement '$ds_{st(d)}/ds_{st(u)}$' with pier spacing 'X_c/b' (where, $ds_{st(u)}$= scour depth at upstream piers, $ds_{st(d)}$= scour depth at downstream pier).

The scour depth at downstream pier with respect to that at upstream piers '$ds_{st(d)}/ds_{(u)}$' are plotted against pier spacing 'X_c/b' as shown in Fig.6. It is observed that the relative scour depth at downstream pier '$ds_{st(d)}/ds_{(u)}$' decreases as the pier spacing 'X_c/b' increases and reaches to a minimum at pier spacing X_c/b=40.

This decrease in '$ds_{st(d)}/ds_{st(u)}$' is due to a decrease in the velocity of flow approaching towards downstream pier. This decrease in approach flow velocity is caused by the shielding of downstream pier by the wakes of upstream piers. At $40<X_c/b\leq 65$, the shielding of the downstream pier by the wakes of upstream piers starts diminishing due to which, the velocity of flow approaching towards the downstream pier increases resulting in an increase the relative scour depth. '$ds_{st(d)}/ds_{st(u)}$' The value of '$ds_{st(d)}/ds_{st(u)}$' reaches to a maximum at pier spacing X_c/b=65. The constant value of '$ds_{st(d)}/ds_{st(u)}$' at $65<X_c/b<90$ indicates the complete disappearance of the shielding effect of wakes of upstream piers and the effect of angle of attack of flow as the total angle of attack produced at pier spacings Z_c/b=9 and X_c/b=90 is less than 7.5º.

5. CONCLUSIONS

It is observed that the scour depths at upstream and downstream piers are maximum at pier spacing X_c/b=10. The arrangement of two upstream piers at lateral pier spacing Z_c/b=9 and downstream pier at longitudinal pier spacing X_c/b=10 produces total effective angle of attack equal to 45° which is identified as the most critical angle of attack producing severe effect on scour depth as found in present study and also reported by Hannah, 1978. At pier spacing X_c/b>10, the scour depth at the downstream is minimum at X_c/b=40. Thereafter, it increases upto pier spacing X_c/b=65 and then remains constant upto X_c/b=90.Based on the results achieved in present investigation, it can be concluded that the downstream pier should be placed at X_c/b=40 since, at this pier spacing, the effect of upstream piers on downstream pier local scour, is minimum

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The Impact of Sustainable Architecture on the Occupants of Office Buildings

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ABSTRACT

Sustainable architecture has the well being of both the environment and occupants as the centre of its focus, where it benefits both simultaneously. This study addresses the impact of sustainable building on the occupantsof office buildings in Malaysia. Embedded cross case case study was conducted on 3 certified green buildings in Malaysia, where sustainable building design elements of the 3 buildings were studied. Surveys were distributed, and interviews were conducted on the occupants of the buildings to see the workability of the design, and how building occupants are affected by it. The result revealed that occupants perceive the IEQ of the green buildings to be affecting their work performance, mood, sense of well being and motivation in a positive manner, and that it is the natural element incorporated in sustainable architecture that affect them positively, as well as moderate stimuli exuded by the IEQ of the green buildings. On the basis of the finding of this study, it was concluded that sustainable architecture has a positive impact on building occupants in green office buildings in Malaysia.

Keywords Sustainable Architecture, Office Buildings, Occupant's Behavior, Psychological Responses, Tropical Climate

INTRODUCTION

There have been extensive bodies of literature on the benefits of nature or natural element in a built environment on the psychological and cognitive behavior of the occupants. Wells (2000) highlighted that exposure to natural scenery has the ability to improve focus, attention span, and working performance of the occupants. The Attention Restorative Theory (ART) developed by Stephen and Rachel Kaplan (1995) also demonstrates a similar result. ART states that contact with natural environment has the effect of reducing mind fatigue caused by constant directed attention, and consequently helps in improving attention, memory, reduce irritability, stress, distractibility, and increase a sense of well being.

Parallel studies have also been done in the field of architecture in the working environments of office buildings. Being a place where people are required to complete a task, increase in productivity and performance is the main goal of most of the building design of this typology (Haynes, 2008). Furthermore, the task being done in this building require constant alert, concentration level, and is a constant burden to one's directed attention, which may lead to a severe damage to one’s well being. Such nature of the activities conducted in office buildings may necessitate this building type to provide a restorative experience to its occupants (Aries, Veitch, & Newsham, 2007).

Environmental psychologists and researchers alike have conducted many investigations of the restorative impact of natural element in a building on the workers occupying office buildings. Heschong et al. (2002) claimed that natural lighting used in any working environment has the ability to improve Indoor Environment Quality (IEQ) of the place, and subsequently improve the performance of its occupants, their long term health, and also their ability to retain memory. It was also proven that, workers in green buildings showed overall higher productivity, on-time delivery, product quality, and a more elevated sense of well-being than those in conventional buildings (Heerwagen, 2000). Other than that, a study done by Abbaszadeh, Zagreus, Lehrer, & Huizenga (2006) revealed that on average, occupants of certified green office buildings rated their environment much more satisfactory than those from conventional office buildings. Based on the literature and studies done by previous researchers, it can be said that there is a positive relationship between sustainable architecture and its impact on its occupants (Deuble & de Dear, 2012; Eichholtz, Kok, & Quigley, 2009; Paul & Taylor, 2008). There has been numerous studies done in the subject, unfortunately, most of the existing studies concerning sustainable buildings in the working environment and its impact upon its occupants are usually only done on settings with different climatic conditions, where the occupants’ preference of building elements differ significantly to those in a more local, tropical context such as the ones available in Kuala Lumpur. Workers occupying office buildings in Malaysia still suffer from inefficient working environment (Khalil & Husin, 2009; NA, 2011), and this may be the reason that they are not reaching their highest potential. Measures should be taken in ensuring that employees can get the most efficient working environment for effective working experience. For this reason, this study is aimed to investigate such relationship in office settings with regards to the local context, which includes the climate condition, and human preferences and behavior.

METHODS

The purpose of this case study is to develop an explanatory model describing the interrelationship between the impacts of sustainable office buildings and the behavior of the workers residing in the buildings. This study consists of 2 types of variables; (i) Building elements in green office buildings, and (ii) Occupants' reacting behaviors towards building elements.

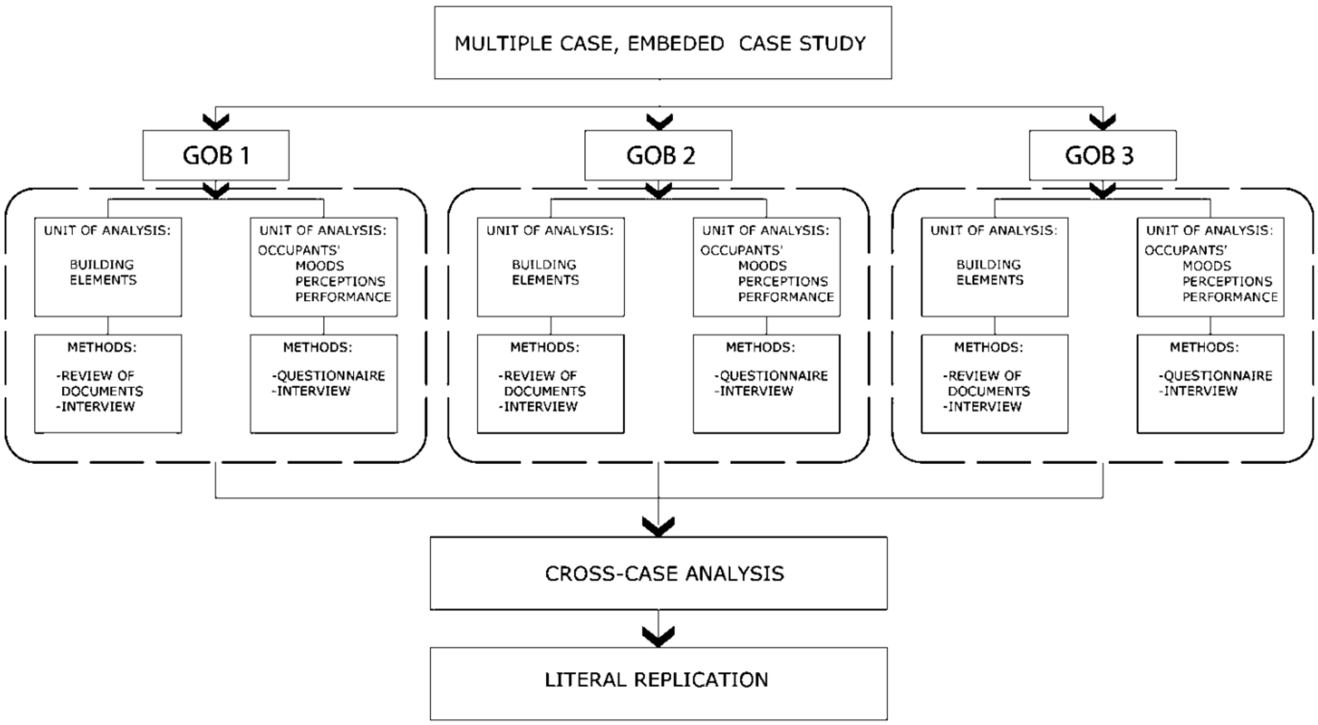

Figure1. Research Methodology Flowchart

Triangulation method combining both qualitative and quantitative methods, such as interviews, surveys, and review of documents were used simultaneously to collect data, to understand how building occupants perceive their environments, and how their perceptions of their environment affect their behavior. The narrative data was transcribed, coded and categorized into themes related to the research questions, while the quantitative data was analyzed using SPSS computer software the outcome of which were further analyzed to find emerging patterns and themes revolving the research question. The data was then tabulated and cross analyzed in the hope of obtaining significant research finding.

SETTING

The study took place in three office buildings in Malaysia in order to study the phenomena within its real-life context including the weather, people's values and ways of life as contributing variables to the outcome. The buildings selected to be used in the case study was based on Green Building rating system, where all 3 buildings used are fully certified green office building certified by the Green Building Index Malaysia. Green office building 1 and 2 are located in the federal administrative centre of Malaysia, Putrajaya, while building 3 is located in Bangi. The surveys and interviews were conducted in the office area of the building to gain a better understanding of how occupants perceive their working environment that, are as close as the actual context. Detailed building elements such as the following will be provided and tabulated to be compared among the 3 buildings;

SAMPLES

The sampling procedures used in this case study are both of convenience and purposive sampling. The sample is divided into two parts following the variable in this study; "the building", and "the occupants' reacting behavior".

THE EFFECT OF BUILDING ON OCCUPANTS

The subjects selected to participate in surveys and interviews to find out their perception of their working environment consisted of convenience sampling, consisting of and restricted to the employees of the 3 selected buildings, who have been working for over a year, where they have had the opportunity to settle down and get used to their working environments enough to be familiar of their surroundings to evaluate it. Participants' demographic data such as age, gender, occupation, year of experience, rank in the organization and ethnicity were also recorded.

GREEN BUILDING ELEMENTS

The sample subjects being interviewed about the building elements in green buildings are of purposive sampling, and consisting of the owners and the officials of the buildings selected.

Data Collection & Procedures .

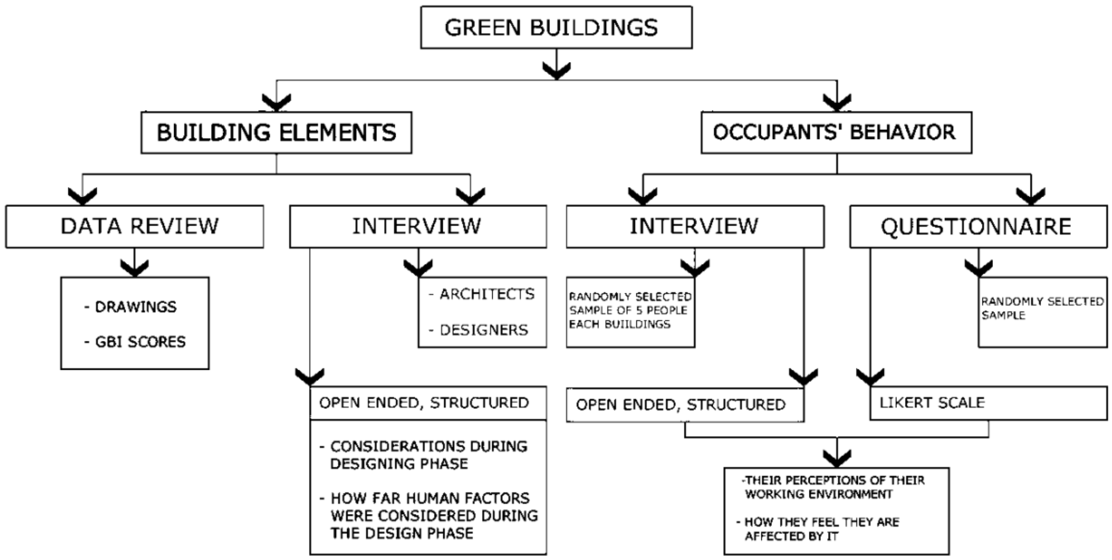

Figure2. Data Collection Procedure

In understanding better the impact of sustainable building on the occupants, the methods used in the data collection process included document reviews, interviews and survey. As there are 2 variables involved in the study, namely “the occupants” and “the building”, data was collected in a respective manner.

THE EFFECT OF BUILDING ON OCCUPANTS

(i) Interview

For the variable “occupants” the data collection procedure consists of surveys and interviews. The interview will be conducted in their offices, and included 5 subjects per building. The interview was conducted individually for the duration of 25 - 30 minutes per person. The interview was that of structured, open ended nature and was aimed at finding out how they perceive their environment, and how they feel like they are affected by it.

(ii) Survey

The survey to evaluate the occupants’ perception of their working environment was distributed. The survey question was developed from an existing post-occupancy evaluation survey, and was altered to be more sensitive to the research questions. The elements measured was their satisfaction level of the IEQ (thermal comfort, air quality lighting, external views, and acoustic quality) of their working environments, their perceived performance with regards to their perception of their environment, and how they feel their well-being, moods and motivations are affected by it.

Survey was distributed to the subjects in the office in the morning, and was collected at the end of the day to avoid from disrupting their work schedule. The survey consisted of 60 questions with answers in the form of Likert scale. The Likert scale will be that of a 5-scale Likert scale, where, -2was the most negative response and 2 was the most positive. The result of the survey will be scored based on the scale score. The higher the score average, the higher the satisfaction level of the occupants. Pilot study was conducted in Green Office Building (GOB) 1, involving 52 numbers of subjects. Alpha Cronbach test was conducted to measure the reliability of the survey questions used. The alpha reliability of the 60 item scale was 0.773, indicating that the scale had a good reliability.

Green Building Elements

For data involving the variable "building", documents related to the building design obtained from the designers and owners of the buildings were reviewed, and interviews with the building owners and officials were conducted to obtain a thorough understanding of the building design of all 3 buildings used in the case study.

DATA ANALYSIS

The Effect of Building on Occupants

In understanding the perception of the occupants of their working environments, both qualitative data and quantitative data were analyzed. For the interview method, subjects' answers were transcribed and coded to be categorized according to research questions, and patterns emerging were observed, analyzed and reported. Meanwhile, the statistical data obtained from the interview were analyzed with the help of SPSS computer software to identify the measure of central tendency, and measure of variability for each category, as well as the significance and reliability of the result. Result will be reported using inferential statistics, and were reviewed and presented per building, and item by item by the researcher. Satisfaction level score of each category (IEQ, moods, and perceived performance) were analyzed separately to answer the research questions.

Green Building Elements

The data collected about the buildings were analyzed in 2 different ways. The documentations such as drawings and other documents were analyzed and converted into text and descriptions of the green building elements that are available in all 3 buildings. The elements available were then tabulated to be cross compared with each other. Data collected through interview with the architects were transcribed and categorized in terms of research questions and emergent themes. Coding method was used to organize interview data into a limited number of themes and issues around the research questions.

Generally, the units of analysis (data collected from the subjects) to be measured in the case study, are as follow; a) Occupants' perception and satisfaction level of the building, b) Occupants' moods and preference towards a space, and c) Occupants' perceived performance levels. The collected data from the case study done on the 3 buildings were compared and a cross-case analysis was done on them, to get the findings of the research. This method is designed with the aim of obtaining literal replication between all 3 buildings selected as the case study.

Finally, all the findings gathered were concluded, and recommendations to improve working environments in office buildings were suggested.

RESULTS

Green Building Elements and Occupants' Satisfaction Level.

The green buildings selected in this study employ sustainable design elements in order to maintain Indoor Environmental Quality (thermal comfort, air quality, lighting quality, acoustic quality, external view) to ensure optimal comfort level in the working environment for the occupants while at the same time minimizing the usage of energy. The design methods employed in maintaining Indoor Environment Quality (IEQ) are as follow;

(a) Thermal Comfort

The 3 buildings are equipped with both passive and active design elements which are employed with the purpose of reducing energy usage, while at the same time providing comfortable environment for the occupants.

Table1. Comparison of Passive Thermal Comfort Design in 3 Green Building Offices

THERMAL COMFORT (Passive Design Element)			
Design Elements	**Green Office Building 1**	**Green Office Building 2**	**Green Office Building 3**
Building Orientation/Shape	1.North-South oriented main facade 2.Minimum no. of windows facing East and West	1.Diamond shape providing shading to lower floors	1.North-South oriented main facade 2.Minimum no. of windows facing East and West
Window Types/Shading Device	**1.Punch hole windows** **2.Shading mechanism;** a) overhang & lightshelves b) louvres	1. Floor-to-ceiling window, surrounding all 4 sides of the elevation.	1.Shading Mechanism 2.Integrated Blinds 3.Reflective Mirror
Window Glazing	1.12mm thick light green tinted glazing	1.Low-E glass 2.Green tinted glazing	1.Double Glazing Windows
Cooling System	1.Water wall in the atrium area 2.Thermal flue chimney	-	-
Roofing	1.Canopy 2.Roof Garden	1.Insulation 2.Roof Garden	1.Insulation 2.River roof
Vegetation	1.Tall Tree Lined Streetscape 2.Vegetation (atrium)	1.Tall Tree Lined Streetscape	1.Lush Landscape around building on Ground Floor (>50%)
Insulation	1.Equipped with 100mm polurethane foam for insulation.	1.100mm thk insulation board (roof & floor slab) 2.PU insulation (vertical upstands)	1.External Wall : 100mm (thermowall) 2.Internal Wall : 50mm(thermowall)

Thermal comfort in the green offices was partly achieved by incorporating passive design elements in the building such as building orientation, window design, window glazing, vegetation and insulation. There are some differences and similarities that are observed in the design measures taken by the 3 office buildings; however, all the design measure was taken with the same purpose; to minimize the infiltration of heat into the building, and consequently minimizing the energy usage for cooling.

Table 2. Comparison of Active Thermal Comfort Design in 3 Green Building Offices

THERMAL COMFORT (Active Design)			
Design Elements	**Green Office Building 1**	**Green Office Building 2**	**Green Office Building 3**
Cooling System	1.Variable Air Volume system 2.Thermal sensor	1.Variable Air Volume system 2.Floor slab cooling. 3.Thermal sensor	1.Variable Air Volume system 2.Floor slab cooling. 3.Thermal sensor

Having minimized the energy usage needed trough employing passive deign in the building, energy used was further reduced by the incorporation of active thermal comfort design. All 3GOB employ Variable Air Volume (VAV) System and thermal sensors both of which maintain the temperature in the building to be at the pre-set level which ranges from 24ºC to 26ºC. Other than VAV system, GOB 2 and GOB 3 utilize floor slab cooling method which increases thermal comfort, energy efficiency and reduces peak-load.

(b) Satisfaction Level of Thermal Comfort

The result obtained from the subjects in this study shows that occupants rate the thermal comfort in their working environment in a positive manner. The 5 point Likert scale was divided into 3 categories. Negative perceptions; "Very Dissatisfied" (-2), and "Dissatisfied" (-1), neither positive nor negative perception, where occupants feel indifferent towards the thermal condition of their working environment; "Normal" (0), and positive perceptions; "Satisfied (1), and "Very Satisfied" (2). Scores were also assigned to each categories where negative scores implies negative perception (-2 : "Very Dissatisfied", -1 : "Dissatisfied"), neutral perception (0 : "Normal), and positive score represents positive perceptions (1 : "Satisfied", 2 : "Very Satisfied"). Mode and Means of the occupants' perceptions are determined according to such scoring system.

The result showed that building occupants in GBO 1 and GBO 3 rated the thermal comfort of their working environment to be positive, where none of the subjects who participated in the survey rated the thermal comfort below "Normal" (0). Meanwhile, in GBO2, 6.5% of the subjects who participated in the survey rated the thermal comfort in the working environment to be dissatisfactory. None of the subjects in all 3 buildings, rated the thermal comfort to be very dissatisfactory (-2), and in all 3 buildings, the score with the highest frequency was “Satisfied” (GOB 1 : 58.5%, GOB 2 : 58.1%, GOB 3 : 76.7%) , followed by “Very Satisfied” (GOB 1 : 37.3%, GOB 2 : 22.6%, GOB 3 : 13.3 %). The mean scores of >1 in GOB 1 and GOB 2 implies that the subjects in those 2 buildings has high satisfaction level towards the thermal comfort of their working environment. The mean score of 1> x > 0 in GOB 2 implies that the subjects in that building, although satisfied with their thermal comfort, their satisfaction level score is significantly lower compared to the other 2 buildings.

Table 3. Occupants’ Satisfaction Level of Thermal Comfort in 3 Green Office Buildings

Occupants' Satisfaction Level Towards Thermal Comfort						
Satisfaction Level	**Frequency**					
	GOB 1 (N = 118)		**GOB 2 (N = 62)**		**GOB 3 (N = 30)**	
	Frequency	**Percentage**	**Frequency**	**Percentage**	**Frequency**	**Percentage**
Very Dissatisfied (-2)	0	0.0%	0	0.0%	0	0.0%
Dissatisfied (-1)	0	0.0%	4	6.5%	0	0.0%
Normal (0)	5	4.2%	8	12.9%	3	10.0%
Satisfied (1)	69	58.5%	36	58.1%	23	76.7%
Very Satisfied (2)	44	37.3%	14	22.6%	4	13.3%
Mean	1.39		0.97		1.03	
Mode	1		1		1	
Std. Deviation	0.614		0.789		0.49	

The interview conducted on 5 subjects in each building revealed the reason the occupants in all 3 buildings rate the thermal comfort positively. The interview outcome revealed that the interviewed subjects in GBO 1, GBO 2, and GBO 3 all have identical answer as to why they have positive perception of the thermal comfort in their working environment. According to 15 subjects interviewed, their positive perception was caused by the moderate temperature of their working environment as a result of carefully controlled indoor environmental condition, where temperature is maintained at 24-26 ^{o}C. According to the all of the 15 subjects interviewed such range of temperature, where it is neither too hot nor too cold, is the optimal thermal comfort level, and was the cause of their positive perception towards the thermal comfort in their working environment.

(a) Air Quality

Due to its climate, in Malaysia optimum working condition where the temperature is at 23-26°C, and the humidity 70-60% is nearly impossible to achieve. For that reason, working environment in Malaysia needs to be fully climatized, where the buildings are fully sealed to prevent outdoor climate from affecting the indoor climate and the comfort level of indoor environment negatively. In the view of such matter, providing natural ventilation in Malaysian office buildings has been proven to be a tricky feat. Such happening can be seen in the ventilation design of GOB 2 and GOB 3, where in order to not compromise the indoor comfort level, the buildings are both fully sealed, to create a fully climatized indoor environment, with optimal comfort level.

Table4. Comparison of Passive Ventilation Design between 3 Green Office Buildings

AIR QUALITY (Passive Design)			
Design Elements	**Green Office Building 1**	**Green Office Building 2**	**Green Office Building 2**
Atrium	**1. Thermal flue chimney effect in the atrium** **2. Fully Climatized Indoor** No natural ventilation is used in other areas	**1. Fully Climatized Indoor** No natural ventilation is used	**1. Fully Climatized Indoor** No natural ventilation is used

GOB 1 allows some design consideration for natural ventilation where the windows in the working area and in the atrium on the ground floor are openable, to allow natural ventilation into the building. Thermal flue stack chimney effect meanwhile, pulls the hot air out of the atrium, allowing natural ventilation to enter the building through the opening, leaving the area with cool temperature, and fresh air.

Table5. Comparison of Active Ventilation Design between 3 Green Office Buildings

AIR QUALITY (Act ive Design)			
Design Elements	**Green Office Building 1**	**Green Office Building 2**	**Green Office Building 2**
Ventilation	**1. Variable Air Volume System (VAV)** **2. CO2 sensors** The more people residing in the building, the greater the density of CO2 in the building, thus the greater the intake of fresh air. **3. Recovery Heat Wheel** assists in meeting all the requirements of IAQ, humidity control and energy saving. **4. Electronic ari cleaners** Further improves the air quality in the building by reducing the level of airborne pollutants.	**1. Variable Air Volume System (VAV)** **2. CO2 sensors** The more people residing in the building, the greater the density of CO2 in the building, thus the greater the intake of fresh air. **3. Electronic air cleaners** Further improves the air quality in the building by reducing the level of airborne pollutants.	**1. Variable Air Volume System (VAV)** **2. CO2 sensors** The more people residing in the building, the greater the density of CO2 in the building, thus the greater the intake of fresh air. **3. Electronic air cleaners** Further improves the air quality in the building by reducing the level of airborne pollutants.

Where it lacks in provision of natural ventilation, the building makes up for with mechanical ventilation. The level of CO_2 in the building is constantly monitored and maintained through VAV system, and fresh air distributed in the building are cleansed w ith electronic air cleaner to further improve the air quality in the building by reducing the level of airborne pollutants.

(b) Satisfaction Level of Air Quality

Table 6. Occupants' Satisfaction Level of Air Quality in 3 Green Office Buildings

Occupants' Satisfaction Level Towards Air Quality						
Satisfaction Level	**Frequency**					
	GOB 1 (N = 118)		**GOB 2 (N = 62)**		**GOB 3 (N = 30)**	
	Frequency	**Percentage**	**Frequency**	**Percentage**	**Frequency**	**Percentage**
Very Dissatisfied (-2)	0	0.0%	0	0%	0	0.0%
Dissatisfied (-1)	2	1.7%	0	0%	0	0.0%
Normal (0)	2	1.7%	9	14.50%	1	3.3%
Satisfied (1)	62	52.5%	29	46.80%	23	76.7%
Very Satisfied (2)	52	44.1%	24	38.70%	6	20.0%
Mean	1.39		1.24		1.17	
Mode	1		1		1	
Std. Deviation	0.614		0.694		0.461	

The scores show that building occupants in GBO 2 and GBO 3 rated the air quality of their working environment to be positive, where none of the subjects who participated in the survey rated the air quality to be below 0 ("Normal"). However, in GBO 1, 1.7% of the subjects who participated in the survey rated the air quality in the working environment to be dissatisfactory. None of the subjects in all 3 buildings, rated the air quality to be at -2 (very dissatisfactory), and in all 3 buildings, the score with the highest frequency was "Satisfied" (GBO 1 : 52.5%, GBO 2 : 46.8%, GBO 3 : 76.7%) , followed by "Very Satisfied" (GBO 1 : 44.1%, GBO 2 : 38.7%, GBO 3 : 20%). Although in GOB 1, 1.7% of the subject rated the air quality to be unsatisfactory, the mean score in GOB 1 was the highest at 1.39, followed by GOB 2 at 1.24, and GOB 3 at 1.17. Mean scores of above 1 ("Satisfied") implies that the subjects in all 3 green office buildings have high satisfaction level towards the air quality in their working environment.

The result from the interview conducted on the subjects in all 3 buildings revealed that in GOB 1 and GOB 3, the respondents are overall satisfied with the air quality in their working environment, however, due to the lack of natural ventilation in GOB 3, the subjects revealed that they feel that the air is a little stale in the building, and that they need more air movement. In GOB 2 meanwhile, the subjects revealed that they experienced the feeling of dryness from the air the first 6 months after they moved to the building, however, after a length of adaptation period, the feeling of dryness are no longer felt. The outcome of the interview also revealed that the source of high satisfaction level of the air quality among the building occupants is due to the fact that they perceive that the air in their working environment is clean and is free of any pollutants as a result of fully sealed building environment.

(a) Lighting Quality

Table 7. Comparison of Passive Lighting Design between 3 Green Office Buildings

LIGHTING QUALITY (PassiveDesign)			
Design Elements	**Green Office Building 1**	**Green Office Building 2**	**Green Office Building 2**
Layout	**1. Permanent Working Area** Concentrated along the perimeter where there is maximum daylight. **2. Secondary Functions** (meeting rooms,store rooms) Relegated to where there is only artificial lighting. **3. More Windows in the North and South** Maximize day lighting while minimizing heat	**1. Open planning and Magnificent Atrium**, optimizes the use of natural lighting.	**1. Open Planning** Workspace all located along window 2. **Working Area Facing the North and South** Maximize daylighting while minimizing heat

Window	**1. Atrium** Glass roof maximizes use of daylight **2. Facade** Windows constitute 25-35% of the façade area depending on the orientation **3. Lightshelf** prevent direct penetration of sunlight.	**1. Atrium** Optimize daylight utilization for each floor **2. Facade** The building has a floor-to-ceiling window, surrounding all 4 sides of the elevation. **3. Lightself** Diffused sunlight 5m into the room, while minimizing glare. **4. Light trough 7th floor** allows areas deep within the building to also utilize natural lighting.	**1. Internal Daylight Reflector** prevent direct penetration of sunlight. **2. Skylight** Allows diffused daylight **3. Facade** Windows constitute 25-35% of the façade area depending on the orientation **4. Lightshelf** Prevent direct penetration of sunlight.

The passive design for lighting in all 3 green office buildings are aimed to maximize the usage of natural lighting all through the building in order to minimize energy used. All 3 buildings employ open planning system where internal partition walls are minimized. Other than that, the 3 green office buildings distribute workspace along the perimeter of the building, where the occupants can get maximum daylight. Another similarity among the three buildings is that the building designs include atrium in order to be able to distribute daylight deep into the building.

In the application of natural lighting in building design in tropical region, the amount of luminance and solar radiation that enters the building are some of the most crucial points to be considered. Unlike buildings in countries with cold climates where vast amount of daylight is a welcome feature in a building, building in tropical climate are prone to the problem of glare.

Other than that, being exposed to the sun, allows solar radiation to enter the building, increasing the temperature within the building, which may cause discomfort within building occupants. For such reasons, the green office building designers takes extra caution in providing the buildings with adequate level of sun shading, in order to maximize daylight, while minimizing glare and solar radiation. GOB 1 & GOB 3 employs orientation technique where the numbers of windows are maximized in North – South orientation, while, in East – West orientation, the number of windows are minimized. Lightshelves are used in all 3 green office buildings in order to provide the working spaces with diffused day lighting, instead of allowing direct sun light into the building, which may cause glare.

The passive lighting design of all the 3 green office buildings are aimed providing the occupants with maximum day light, while exposing them to minimum solar radiation in order to maintain the comfort level in the workspace, while at the same time reducing energy used for lighting and cooling. With the application of passive design to maximize daylight usage, energy consumption is greatly reduced in green office buildings.

Active lighting design further helps in reducing energy usage in providing adequate lighting condition for building occupants. However, office buildings cannot rely solely on day lighting to function. For that reason, active design lighting is used to ensure efficient energy consumption. Photo sensors control lighting near the window automatically switch off when there is sufficient daylight (350 lux), while occupancy sensors detects movements, and automatically switches off lighting if no motions are detected. All 3 buildings are completed with both photo and motion sensors.

Table 8. Comparison of Active Lighting Design between 3 Green Office Buildings

LIGHTING QUALITY (Active Design)			
Design Elements	**Green Office Building 1**	**Green Office Building 2**	**Green Office Building 2**

Lighting System	**1.Photo sensors** Controls lighting near the window automatically switch off when there is sufficient daylight (350 lux). **2. Occupancy sensor** lights will be switched of if no motions are detected. **3. Manual switch to turn lights on manually** 4. **Use of energy efficient lamps and fittings**	**1. Photo sensors** Controls lighting near the window automatically switch off when there is sufficient daylight (350 lux). **2. Manual switch to turn lights on manually** **3. Task light at individual desks.**	**1. Photo sensors** Controls lighting near the window automatically switch off when there is sufficient daylight (350 lux). **2. Motion Sensor** **3. Thermal Movement detection** **4. Manual On - off** **5. Use of energy efficient lamps and fittings** **6. Task light at individual desks.**

(b) Satisfaction of Lig hting Quality

Table 9. Occupants' Satisfaction Level of Lighting in 3 Green Office Buildings

Occupants' Satisfaction Level Towards Lighting						
Satisfaction Level	**Frequency**					
	Green Office Building 1 (N = 118)		**Green Office Building 2 (N = 62)**		**Green OfficeBuilding 3 (N = 30)**	
	Frequency	**Percentage**	**Frequency**	**Percentage**	**Frequency**	**Percentage**
Very Dissatisfied (-2)	0	0.0%	0	0%	0	0.0%
Dissatisfied (-1)	1	0.8%	2	3%	0	0.0%
Normal (0)	5	4.2%	10	16.10%	0	0.0%
Satisfied (1)	70	59.3%	33	53.20%	19	63.3%

Very Satisfied (2)	42	35.6%	17	27.40%	11	36.7%
Mean	1.3		1.05		1.37	
Mode	1		1		1	
Std. Deviation	0.589		0.756		0.94	

The result of the survey conducted on the subject shows that only building occupants in GBO 3 rated the lighting quality of their working environment to be positive, where none of the subjects who participated in the survey rated the lighting quality to be below 0 ("Normal"). However, in GBO 1, 0.8% of the subjects who participated in the survey rated the lighting quality in the working environment to be dissatisfactory, while in GOB 2 3% of the occupants are dissatisfied with the lighting quality. None of the subjects in all 3 buildings, rated the lighting quality to be at -2 (very dissatisfactory), and in all 3 buildings, the score with the highest frequency was "Satisfied" (GBO 1 : 59.3%, GBO 2 : 53.2%, GBO 3 : 63.3%) , followed by "Very Satisfied" (GBO 1 : 35.6%, GBO 2 : 27.4%, GBO 3 : 36.7%). Although in 2 office buildings, 0.8% and 3% of the occupants rated the lighting condition to be dissatisfactory, the >1 mean scores of all the 3 green office buildings (GOB 1: 1.3, GOB 2: 1.05, GOB 3: 1.37) show that in average, occupants of the buildings have high satisfaction level with the lighting quality of their working environment.

The interview conducted on the building occupants revealed that the cause of their high satisfaction level of the lighting quality in their working environment, was that according to the occupants in all 3 buildings, they prefer natural day lighting over artificial lighting, and having access to natural day lighting, they claim that they experience a feeling of lightness in their working environment which improves their mood. In GOB 2 however, the 3% of the subject which rated the lighting quality to be dissatisfactory claim that due to the design of the façade, which are of full glass facade, the amount of lighting the occupants are exposed to can be too extreme, where it can cause glare.

(a) External Views

Other than tree-scrapes along the front façade of the building, there is no special provision of landscape in GOB 1. In GOB 2, the landscaping is located on the ground floor surrounding the building perimeter, while GOB 3 allows more than 50% of the building footprint to be landscaping area.

Located in federal administrative centre of Malaysia, Putrajaya, most of the occupants in GOB 1 and GOB 2 claims that the view that they are mostly exposed to are those of buildings (GOB 1 : 51.7%, GOB 2: 47.3%), traffic and roads (GOB 2: 17.8%, GOB 1: 22.1%) and parking areas (GOB 1: 16.1%, GOB 2: 19.8%) surrounding them. Only small percentage of occupants in GOB 1 and GOB 2 reveal that they have access to nature views. (GOB 1 : 14.4%, GOB 2: 10.8%).

Table 10. Comparison of External Views Provided in 3 Green Office Buildings

External Views			
Design Elements	**Green Office Building 1**	**Green Office Building 2**	**Green Office Building 3**
Landscaping	**Turf planted around building** - No special provision	**Landscape around building on Ground Floor** Provides aesthetic views while helping to cool down the area	**Lush Landscape around building on Ground Floor (>50%)** Provides aesthetic views while helping to cool down the area

In GOB 3, which is located in Bangi, in a less crowded area where more than 50% of the building foot print is allocated for lush green landscape, the 57.4% of the occupants revealed that they are majorly exposed to views of nature in their working environment every day.

(b) Satisfaction Level of External Views

Table 11. Occupants' Satisfaction Level of External Views in 3 Green Office Buildings

Occupants' Satisfaction Level Towards External Views						
Satisfaction Level	**Frequency**					
	Green Office Building 1 (N = 118)		**Green Office Building 2 (N = 62)**		**Green Office Building 3 (N = 30)**	
	Frequency	**Percentage**	**Frequency**	**Percentage**	**Frequency**	**Percentage**
Very Dissatisfied (-2)	0	0.0%	0	0.0%	0	0.0%

Dissatisfied (-1)	3	2.5%	0	1.6%	0	0.0%
Normal (0)	13	11.0%	7	11.3%	1	3.3%
Satisfied (1)	81	68.6%	40	64.5%	23	76.7%
Very Satisfied (2)	21	17.8%	15	24.2%	6	20.0%
Mean	1.02		1.13		1.17	
Mode	1		1		1	
Std. Deviation	0.627		0.586		0.461	

The scores obtained from the survey show that only building occupants in GBO 3 fully rated the external view of their working environment to be positive, where none of the subjects who participated in the survey rated the external view to be below 0 ("Normal"). However, in GBO 1, 2.5% of the subjects who participated in the survey rated the external view in the working environment to be dissatisfactory, while in GOB 2, 1.6% of the subjects are dissatisfied with their external views. None of the subjects in all 3 buildings, rated the external view to be at -2 (very dissatisfactory), and in all 3 buildings, the score with the highest frequency was "Satisfied" (GBO 1 : 68.6%, GBO 2 : 64.5%, GBO 3 : 76.7%) , followed by "Very Satisfied" (GBO 1 : 17.8%, GBO 2 : 24.2%, GBO 3 : 20%). Mean score of the 3 buildings of above 1 ("Satisfied") implies that the subjects in all 3 green office buildings have high satisfaction level towards the external view in their working environment.

The interview conducted on the participants reveals the reason that GOB 3 has the highest mean score out of the 3 buildings. It was revealed that the more the occupants are connected to nature elements, the higher their satisfaction level with their surrounding, which means that the more they are exposed to the view of nature, the more content they are of their surroundings.
This explains the reason that the occupants in GOB 3, which has more provision of landscaping area than GOB 1 and GOB 2, has higher satisfaction level compared to the other 2 buildings.

3.1.5 (a) Acoustic Performance

Among the 3 green office buildings, only GOB 3 considered acoustical performance as part of their building design. The building is equipped with double glazed window, which not only acts as heat insulation, but also act as sound insulation to ensure a conducive working environment.

Table 13. Comparison of Acoustic Design between 3 Green Office Buildings

Acoustic Performance			
Design Elements	**Green Office Building 1**	**Green Office Building 2**	**Green Office Building 3**
Sound Proofing	-	-	**Double glazed window**

3.1.5 (b) Satisfaction Level of Acoustic Performance

Table 14. Occupants' Satisfaction Level towards Acoustic Performance in 3 Green Office Buildings

Occupants' Satisfaction Level Towards Acoustic Quality						
Satisfaction Level	**Frequency**					
	Green Office Building 1 (N = 118)		**Green Office Building 2 (N = 62)**		**Green Office Building 3 (N = 30)**	
	Frequency	**Percentage**	**Frequency**	**Percentage**	**Frequency**	**Percentage**
Very Dissatisfied (-2)	0	0.0%	0	0.0%	0	0.0%
Dissatisfied (-1)	4	3.4%	1	1.6%	0	0.0%
Normal (0)	19	16.1%	16	25.8%	3	10.0%
Satisfied (1)	74	62.7%	42	67.7%	20	66.7%
Very Satisfied (2)	21	17.8%	3	4.8%	7	23.3%
Mean	0.95		0.76		1.13	
Mode	1		1		1	
Std. Deviation	0.69		0.564		0.571	

The result of the survey conducted on the subject shows that only building occupants in GBO 3 fully rated the acoustic quality of their working environment to be positive, where none of the subjects who participated in the survey rated the acoustic quality to be below 0 ("Normal"). However, in GBO 1, 3.4% of the subjects who participated in the survey rated the acoustic quality in the working environment to be dissatisfactory, while in GOB 2, 1.6% of the subjects are dissatisfied with their acoustic quality. None of the subjects in all 3 buildings, rated the acoustic quality to be at -2 (very dissatisfactory), and in all 3 buildings, the score with the highest frequency was "Satisfied" (GBO 1 : 68.6%, GBO 2 : 64.5%, GBO 3 : 76.7%) , followed by

"Very Satisfied" (GBO 1 : 17.8%, GBO 2 : 24.2%, GBO 3 : 20%). The mean score of GOB 3 was revealed to be the highest at >1, while the other 2 buildings had mean scores of below 1. This implies that the occupants of GOB 3 have the highest satisfaction level of the acoustic quality of their working environment, as compared to the other 2 buildings. This finding may be linked to the design of the building itself, where only GOB 3 has incorporated considerations of acoustic quality in the building design.

The interview however revealed that the subjects in all 3 buildings all have high satisfaction level of the acoustic quality in their working environment. However, the reason of their high satisfaction level is unrelated to the design provision of acoustical insulation in the building or the lack there of. The interview revealed that the subjects' high satisfaction levels towards the acoustical quality are linked with their perception of the geographical location of their office building. According to the subjects, the office buildings they currently work in are much more secluded, thus much quieter than their previous working environments. Such comparison to their previous working environment which were located in a more crowded area, closer to heavy traffic, and which they perceive to be significantly noisier, leads the subject to perceive their current working environment to be more acoustically pleasing, regardless of any design provision on acoustical performance.

Effect of Indoor Environment Quality on Occupants' Productivity, Mood, Sense of Well-Being, and Motivation

Other than finding out the subjects' perception of their working environment, the survey and interview were also aimed at understanding how the subjects perceive their working environment to be affecting them. The occupants' reaction to their working environments observed through the questionnaire and the interview are occupants' perceived productivity, perceived mood, perceived sense of wellbeing, and perceived motivation to work.

The Effect of Green Office Building on Occupants' Perceived Productivity

Table 15. Subject's Perceived Increase of Productivity in Relation to Their Working Environment

Subject's Perceived Increase of Productivity in Relation to Their Working Environment						
Perceived Increase in Productivity (%)	**Frequency**					
	Green Office Building 1 (N = 118)		**Green Office Building 2 (N = 62)**		**Green Office Building 3 (N = 30)**	
	Frequency	**Percentage**	**Frequency**	**Percentage**	**Frequency**	**Percentage**
-20% (1)	0	0.0%	0	0.0%	0	0.0%
-10% (2)	0	0.0%	0	0.0%	0	0.0%
-5% (3)	0	0.0%	0	0.0%	0	0.0%
0% (4)	3	2.5%	12	19.4%	2	6.7%
5% (5)	49	41.5%	14	22.6%	13	43.3%
10% (6)	37	31.4%	19	30.6%	10	33.3%
20% (7)	29	24.6%	17	27.4%	5	16.7%
Mean	5.78 (5% - 10%)		5.66(5% - 10%)		5.6(5% - 10%)	
Mode	5 (5%)		6 (10%)		5 (5%)	
Std. Deviation	0.849		1.086		0.855	

The Likert scale used in finding out occupants' perceived increase in productivity is that of 7-point Likert scale, ranging from "1" which represents -20% productivity increase (or 20% decrease) to "7" representing 20% productivity increase. In all 3 green office buildings, it was observed that none of the subjects feel like their performances are affected negatively by their working environment. In GOB 1 and GOB 2 the score with the highest frequency was 5% productivity increase followed closely by 10% productivity increase. Meanwhile, occupants in GOB 2 perceive that their productivity are even more positively affected than the other 2 buildings, where the score with the highest frequency is 10% productivity increase followed closely by 20% productivity increase.

Mean scores of $5 < x < 6$, where the mean lies between 5% increase and 10% increase, implies that the subjects perceive their working environment to be affecting productivity positively.

The interview revealed similarity among the subjects in all 3 buildings, which stated that the optimal comfort level resulting from sustainable building design was what they perceive to be affecting them in a positive manner. Furthermore, they also stated that the IEQ elements to be affecting their productivity the most are; thermal comfort, air quality, and lighting quality. There is also a recurring pattern where subjects in all 3 buildings stated that external view provides them with "a sense of connectivity with the outside world", “medium of stress release”, giving them occasional short breaks from their task, which they perceive to be a factor that indirectly increases their productivity.

The Effect of Green Office Building on Occupants’ Perceived Mood

The Likert scale used in the survey question to find out how occupants perceive their working environment to be affecting their mood is a 5-point Likert scale ranging from -2 (most negative perception) to +2 (most positive perception). The result of the survey revealed that none of the occupants in the 3 buildings have negative perception on how the building affect their mood, where 0% of the respondents rate the effect of their working environments as -1 or -2.

Table16. Occupants' Perception of How the Building Affect Their Mood

Occupants' Perception of How the Building Affect Their Mood						
Occupants' Perception	**Frequency**					
	Green Office Building 1 (N = 118)		**Green Office Building 2 (N = 62)**		**Green Office Building 3 (N = 30)**	
	Frequency	**Percentage**	**Frequency**	**Percentage**	**Frequency**	**Percentage**
Really Disturbs (-2)	0	0.0%	0	0.0%	0	0.0%
Disturbs (-1)	0	0.0%	0	0.0%	0	0.0%
No Effects (0)	3	2.5%	7	19.4%	3	10.0%
Improves (1)	77	65.3%	40	50.0%	21	70.0%
Really Improves (2)	38	32.2%	15	30.6%	6	20.0%
Mean	1.3		1.11		1.1	
Mode	1		1		1	
Std. Deviation	0.512		0.704		0.548	

In all 3 buildings the score with the highest frequency was 1, “Improves” (GOB 1: 65.3%, GOB 2: 50%, GOB 3: 70%) followed by the score 2 “Really Improves” (GOB 1: 32.2%, GOB 2:

30.6%, GOB 3: 20%). The mean score of $1 < x < 2$ implies that occupants perceive that the building elements in green office building does not affect their moods negatively, instead, it has the power of improving their moods while they are in their work place.

From the interview, it was revealed that there are 3 repetitive patterns in the answers of the subjects of the three buildings about the source of their positive perception of the effect of their working environment on their moods. Firstly, according to the subjects, their mood is affected positively by “the feeling of lightness” exuded by the indoor environment of the buildings, which resulted from optimal usage of natural daylight. Secondly, the optimal comfort level of the indoor environment quality of the building (mostly focusing on thermal comfort, lighting, air quality) also contributes to improving the mood of the subjects. Finally, the subjects claim to feel a sense of pride about the green building status of the office they work in, and such impression also contributes to the improvement of subjects’ mood and feeling in their workplace.

The Effect of Green Office Building on Occupants’ Perceived Sense of Well-Being

Similar to the previous survey question, the Likert scale used in the survey question to find out how occupants perceive their working environment to be affecting their sense of well-being is a 5-point Likert scale ranging from -2 (most negative perception) to +2 (most positive perception). The result of the survey revealed that, similar to the effect of their working environment on their moods, none of the occupants in the 3 buildings have negative perception on how the building affect their sense of well-being, where 0% of the respondents rate the effect of their working environments as -1 or -2.

In all 3 buildings the score with the highest frequency was 1, “Improves” (GOB 1: 66.9%, GOB 2: 48.4%, GOB 3: 73.3%) followed by the score 2 “Really Improves” (GOB 1: 30.5%, GOB 2: 32.3%, GOB 3: 16.7%). The mean score of $1 < x < 2$ implies that occupants perceive that the building elements in green office building does not affect their sense of well-being negatively, instead, they feel like their well-being is significantly improved by the green building elements in their working environment.

Table 17. Occupants' Perception of How the Building Affect Their Sense of Well-Being

Occupants' Perception of How the Building Affect Their Sense of Well-Being						
Occupants' Perception	**Frequency**					
	Green Office Building 1 (N = 118)		**Green Office Building 2 (N = 62)**		**Green Office Building 3 (N = 30)**	
	Frequency	**Percentage**	**Frequency**	**Percentage**	**Frequency**	**Percentage**
Really Worsen (-2)	0	0.0%	0	0.0%	0	0.0%
Worsen (-1)	0	0.0%	0	0.0%	0	0.0%
No Effects (0)	3	2.5%	12	19.4%	3	10.0%
Improves (1)	79	66.9%	30	48.4%	22	73.3%
Really Improves (2)	36	30.5%	20	32.3%	5	16.7%
Mean	1.28		1.13		1.07	
Mode	1		1		1	
Std. Deviation	0.504		0.713		0.521	

From the interview, it was revealed that only the subjects of GOB 2 and GOB 3 perceive that their sense of well-being is affected by the buildings. According to the subjects from those 2 buildings, what they perceive to be affecting their well-being positively is the adequate indoor environmental quality resulting from the building design, where the thermal comfort, lighting quality and air quality are at optimal level, where it is not at opposing extreme ends where it is either too excessive or insufficient. The subjects interviewed in GOB 1 however, do not perceive their environment to be affecting their well-being in any way. According to them, what affect their sense of well-being is what they do outside work, and is completely unrelated to the indoor environment quality or the green building elements in their working environment.

The Effect of Green Office Building on Occupants' Perceived Motivation to Work

The result from the survey revealed that occupants in GOB 1, GOB 2, and GOB 3, all rated the effect of the building to be affecting their motivation to come to work positively. 0%of the subjects rated the effect to be negative (-1 – “Decrease”, -2 – “Really Decrease”) in the survey distributed to them.

In all 3 buildings the score with the highest frequency was 1, “Increase” (GOB 1: 57.6%, GOB 2: 51.6%, GOB 3: 66.7%) followed by the score 2 “Really Improves” (GOB 1: 39.8%, GOB 2: 30.6%, GOB 3: 23.3%). The mean scores of $1 < x < 2$ imply that occupants perceive that the building elements in green office building to have a positive impact on their motivation, where the building improves their motivation to go to work.

Table 18. Occupants' Perception of How the Building Affect Their Motivation to Work

Occupants' Perception of How the Building Affect Their Motivation to Work						
Occupants' Perception	**Frequency**					
	Green Office Building 1 (N = 118)		**Green Office Building 2 (N = 62)**		**Green Office Building 3 (N = 30)**	
	Frequency	**Percentage**	**Frequency**	**Percentage**	**Frequency**	**Percentage**
Really Decrease (-2)	0	0.0%	0	0.0%	0	0.0%
Decrease (-1)	0	0.0%	0	0.0%	0	0.0%
No Effects (0)	3	2.5%	11	17.7%	3	10.0%
Increase (1)	68	57.6%	32	51.6%	20	66.7%
Really Increase (2)	47	39.8%	19	30.6%	7	23.3%
Mean	1.37		1.13		1.13	
Mode	1		1		1	
Std. Deviation	0.536		0.689		0.571	

Interviews conducted on the subject meanwhile revealed split responses, where 60% of the subject interviewed in each building perceive their environment to be affecting their motivation to go to work positively, while the other 40% stated that the building has no effect whatsoever on their motivation to go to work every day. Among the 60% who perceive their environment to be affecting their motivation positively, a pattern was discovered where they asserted that the reason of such positive perception resulted from optimal comfort level in their working environment involving 3 IEQ elements; thermal comfort, lighting quality, and air quality. Other than that, they also stated that “attractive working environment with plenty of day lighting” to be the cause of their increased motivation. The 40% of the subjects who claimed to be unaffected by their work environment stated that their motivation to go to work every day is something that they have to build up internally, and has nothing at all to do with the condition of their working environment.

DISCUSSIONS

Occupants' Perceptions towards Green Office Buildings

Both data from survey and interview revealed that in general, occupants of all 3 GBI certified building have positive perception towards their working environment. Basing on the subjects' high satisfaction level of the working environment in their office buildings, it can be said that the sustainable design approach taken to obtain optimal indoor environmental quality, while at the same time minimizing the energy used, was proven to be successful. Overall, the subjects rated the Indoor Environmental Quality (IEQ) which consists of thermal comfort, air quality, lighting quality, acoustical performance, and external view to be highly satisfactory.

Employing VAV system, floor slab cooling and fully climatized indoor environment succeeded in creating optimal thermal comfort for the occupants, where the resulting moderate average temperature of 24oC was perceived to be highly satisfactory by occupants. The same can be said with air quality, where in average, occupants are satisfied with condition of ventilation in their working environment. However, fully climatized indoor, which was obtained by sealing off the building from outside climate, completely detaching building occupants from natural ventilation, causes slight dissatisfaction among the building occupants due to the lack of air movement resulting from it. Still, fully climatized indoor was also perceived by the building occupants to be able to ensure that no pollutants enter the building, which leads to their high satisfaction level towards the air quality. Occupants also have high satisfaction level towards the lighting quality of the building. It was also discovered that building orientation is crucial in obtaining high satisfaction level. Occupants in buildings without such design technique rated the natural lighting used in the building to be either too bright or too dim. In moderate lighting, occupants associate "the feeling of lightness" from natural lighting with improved mood and performance. Both external views and acoustic quality of the 3 buildings were also perceived positively by the building occupants; however the satisfaction score obtained by the survey was not as high as the other 3 IEQ elements (thermal comfort, air quality and lighting quality). The small percentage of the subjects who responded with negative perception were subjects that were exposed to stimuli overload / depravation such as; fresh air insufficiency, extreme lighting condition, lack of external view, and poor acoustic performance.

Overall, sustainable building design employed in the 3 buildings was perceived positively by the building occupants where in average, they have high satisfaction level of their working environment. According to them, the building design allows for optimal indoor environmental quality, creating a comfortable, effective working environment for them.

Occupants' Perception of How Green Office Buildings Affect Their Productivity, Mood, Sense of Well-Being, and Motivation This study looks into the impact of sustainable office building on occupants' productivity, mood, sense of well-being, and motivation to go to work. Overall, the subjects who participated in this study not only have high satisfaction level towards the building, but also perceive the building to be affecting them positively.

The subjects perceived that their productivity and mood are more positively affected by the building compared to their sense of well-being and motivation to go to work. They uniformly agree that they perceive the building to have positive impact on their productivity and mood, whereas, their response to the impact of the building on their sense of well-being and motivation are more varied. The productivity and mood of the occupants are both perceived to be affected positively by thermal comfort, air quality, and lighting quality of the building. Their moods in particular, are affected by the lighting quality, where "the feeling of lightness" caused by optimal usage of day lighting has the most positive impact on the occupants' moods.

Unlike perceived productivity and moods where the subjects' responses are uniform, the response of subjects' perceived sense of well-being and motivation are varied, where the response are divided into two; "affected positively", and "not affected by the building". However, none of the subjects perceive the buildings to be affecting their sense of well-being and motivation negatively. Subjects who perceive their well-being to be affected positively reported that the optimal level of 3 elements of IEQ (thermal comfort, air quality and lighting quality) are what affect the subjects positively, while they perceive their motivation to go to work to be affected positively by attractive and comfortable working environment. The subjects who claim that their well-being and motivation to go to work are unaffected by the building have similar opinion that both are dependent on the things they do outside of work, and are completely unrelated to the condition of their working environments.

Although the Indoor Environmental Quality (IEQ) consists of 5 elements namely; "Thermal Comfort", "Air Quality", "Lighting Quality", "Acoustic Quality" and "External Views", the subjects interviewed perceived that their productivity, mood, sense of well-being, and motivation to go to work are affected most positively by 3 IEQ elements; "Thermal Comfort", "Air Quality", "Lighting Quality". Meanwhile, according to them, although "Acoustic Quality" and "External Views" have some positive effect on their productivity, mood, sense of well-being, and motivation to go to work, their effects is not as weighty as the previous 3 IEQ elements.

CONCLUSION

Research show that sustainable building design has a significant effect on building occupants. Indoor environmental quality elements such as thermal comfort, air quality, lighting quality, external view, and acoustic quality all have impact on the occupants residing within the building. It was found that green building design creates optimal indoor environmental quality which provides occupants with comfortable and conducive working environment.

It was proven that occupants perceive green office buildings in a positive manner, where they have high satisfaction levels towards the indoor environmental quality of their working environments. In addition to their positive perception, they also deem the green office buildings they work in to be impacting them positively, where it increases their productivity and motivation, while at the same time, improving their mood and sense of well-being.

Thus, it can be concluded that the sustainable building design employed in Malaysia succeeded in creating a comfortable, healthy working environment for its occupants, where they can thrive and reach their maximum potential, while at the same time reducing the negative impact on the environment. For that reason, it imperial that measures are taken to commit to creating an improved working/learning/living environment which cares for the well-being of both human and the environment, where both can co-exist in harmony.

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Author's Profile

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Sati Sekar Kinanthi is currently completing her masters in architecture, focusing on the impact of sustainable buildings on the occupants of office buildings in Malaysia. Graduated from MARA University of Technology in B.Sc. Architecture, she has had 4 years of formal education in architecture and 3 years of working experience as an architect prior to conducting her research in sustainable buildings. Indonesian by nationality, she spent her life moving around the globe. She spent 9 years growing up in Indonesia, 4 years in Japan, and 14 years in Malaysia. She is an environmentalist, and is a firm believer that architecture is one way to save the environment. On the same note, she also believes that architects have the responsibilities to educate the public about the environment. Other than that, she is passionate about writing. She considers writing a good tool of making herself heard. To date, she has written 2 dissertations on architecture; "Architecture & Psychology" and"Malaysian Architecture".

Modular Construction: A Sustainable Construction Technology

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ABSTRACT

Modular building is an advanced architectural construction method. 'Permanent Modular Construction' (PMC) is a part of modular construction methods which found to be innovative and sustainable construction delivery method. This method of construction basically performed off using lean manufacturing technique for prefabricating single or multi story building construction in transportable module sections to the actual site location. Designing of such system is highly complex process and demands a system atic approach. In PMC use of wood, steel, or concrete & fly ash can be applied, considering fly ash in concrete increases its workability and enhances thermal performance, additionally fly ash concrete blocks replaced the traditional clay blocks because they does not contains expansive soil cause walls and floors to crack with fluxes of temperature and humidity. This paper presents a brief introduction basic principles and application fields of PMC. The use if PMC is found motivating because of over riding client requirements for speedy (50% faster than conventional construction) construction, quality improvement and for early return of their investment. There is a noticeable trend to use modular construction in social housing, where period of construction c the economy of production scale and to reduce disruption in congested areas of a city.

Keywords: Advanced modular construction, PMC, Sustainable, Energy efficient.

1.0 INTRODUCTION

Permanent modular construction (PMC) depends on modern manufacturing advanced techniques to deliver high quality buildings in approximately three times faster than conventional construction allowing the owners to get a return against their investment more quickly. PMC can also deliver a more energy efficient building that will cost less to operate as compared in site-built structure and being constructed in a more efficient, environmentally sustainable manner.

PMC is an innovative, sustainable construction delivery method utilizing off-site (prefabrication), lean manufacturing techniques to prefabricate single or multi-story whole building solutions in deliverable module sections. PMC buildings are constructed in a safe and controlled setting by taking in use of wood, steel or concrete.

PMC modules can be utilize into site built projects or stand alone as a turn-key solution and can be moved to target location by using mechanical, electrical & plumbing (MEP) fixtures and interior finishes within a very little time, with less, wastage and higher quality controlled in comparison to projects running over on-site construction.

Many industries regularly use permanent modular construction studies (schools, banks, restaurants, hospitals, medical clinics, day care centers and correctional facilities etc.
The survey revealed that 93%, modular buildings components generally fabricated off-site in a controlled environment, and moved with means of different transportation and assembled at the final location of building, [1].

These may be different component of entire building or be component of subassemblies of large structures. Conditionally, modular contractors work with traditional general contractors to leverage the resources and advantages of each type of construction.

PMC are constructed to meet or exceed the same building standards and codes as on site built structures and the same architect specified materials used for conventionally constructed buildings are used in modular construction. Also PMC can have as many stories as per building codes. Unlike relocatable building, PMC structures are intended to remain in one location for their useful life duration.

Many adopters are using prefabrication building processes on a wide variety of commercial building projects. Specifically, respondents are using this technology mostly on healthcare facilities, college buildings, dormitories and manufacturing buildings.

The main fields of application of PMC production generally consists of the following, [2, 11]:

a) Construction of Private houses, Social houses.
b) Construction of ‘Apartments and mixed use buildings’.
c) Construction of ‘Educational sector and student residences’.
d) Construction of ‘Key worker accommodation and sheltered housing’.
e) Public sector buildings like prisons and Ministry of Defence (MoD) buildings.
f) Health sector buildings.

g) Hotels.

These respondents see the most future opportunity in healthcare facilities (14%), hotels and motels (11%), commercial warehouses (11%) and other building types (10%) that included data centers, prisons, power plants and oil refineries, [3]. Figure 1&2, shows current drivers who are using prefabrication technology and percentage of users using prefabrication technology in U.S.

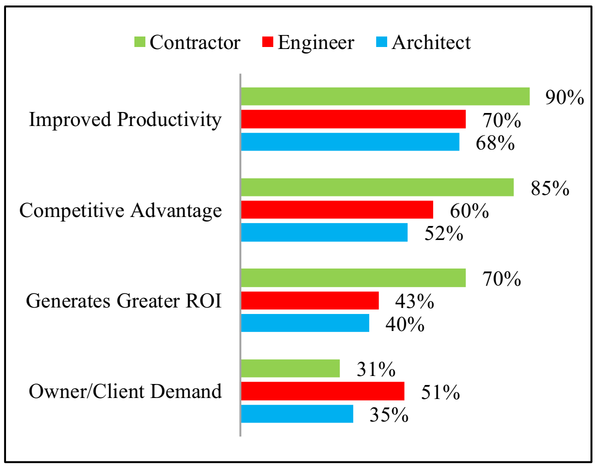

Figure 1: Current Drivers to Use of Prefabrication [Source: McGraw-Hill Construction, 2011]

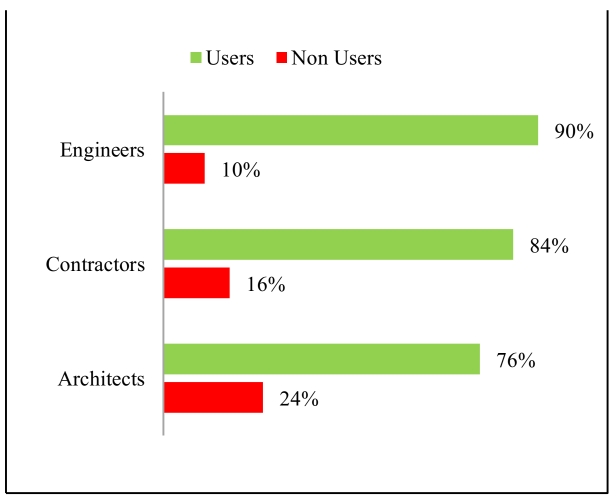

Figure 2: Percentage of Prefabrication/ Modularization Users in 2011[Source: McGraw-Hill Construction, 2011]

These opportunities vary with type of usage. Within a specific building, prefabrication and modular construction are used in different areas but most often in the building superstructure (27%), mechanical, electrical and plumbing (MEP) systems (21%) and exterior walls (20%), [3]. When deciding whether or not to use prefabrication or modularization, the most important factor is the job site accessibility (58%) followed very closely by the number of stories of buildings (53%) and the type of building exterior (52%), [3].

2.0 BASIC PRINCIPLES

PMC structures are likely make to remain at one location throughout their useful life. As PMC is a subdivision of modular construction and modular construction basically refers to 3-dimensional building modules that are fabricated at off-site and then transported back to the usable site/location to prepare the entire building.

All the customer demands are taken into consideration and having the objective in responding to the customer requests, they typically operate as general contractors on projects, coordinating the delivery, installation, site work and finish of the building.

Primarily construction is processed indoors away from harsh weather conditions preventing damage to the building materials and allowing builders to work in comfortable conditions within stipulated period of time. A production scheme for PMC is shown in Figure 3.

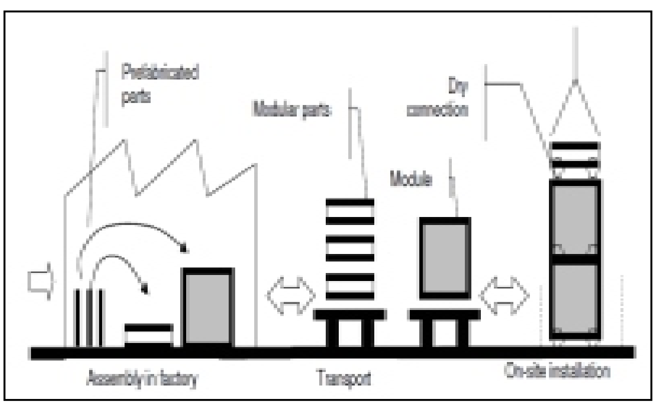

Figure 3: Modular Construction Production Scheme [4]

PMC may be either 'Type V (wood frame, combustible)' or 'Type II (steel, concrete, non-combustible)' and can have as many stories as building codes allow.

PMC structures can be either single story or multi storey with desired strength as per standards of codes. A typical assembling process of a modular hospital building is shown in *Figure 4.*

Modular construction of house can be classified as [4,12]:

a) One Block House

b) Multiple Blocks House

c) Modular House Assembled on Site

3.0 ADVANTAGES

Now day's PMC or modular buildings are not just temporary construction trailers and portable module manufacturing process. There are many more applications for modular building solutions, these are useful in permanent housing "Remote and urban areas", retail space solutions, municipal facilities, industrial site offices and special event requirements. There are hundreds of end users benefits available from ease of use and flexibility that modular construction attain. Attractive prefabricated buildings can be of any size, have multiple stories and custom designed to meet specific needs.

The PMC is a technique which has various advantages that contribute to the lean construction and build on the lean principles foundation.

Some of the advantage of permanent modular construction is [5]:

a) Enhanced speed of the overall construction process.

b) Waste minimization throughout the whole construction process.

c) Increased labor productivity.

d) Improved work supervision.

e) Less environmental impacts such as weather.

f) Smoother construction schedules.

g) Less material storage and handling requirements.

h) Increase worker safety and less risk exposure.

The above advantages of PMC have become more popular due to their contribution to the concepts of recycling the materials usage in the process and the Building Information Modeling (BIM) that improves the communication aspect of lean within prefabricated construction. Thus, PMC is very useful in lean construction process when it comes to increasing productivity and reducing/eliminating wastage. As there is considerable difference between the process of Modular construction schedule and on site built construction schedule, shown in figure 5.

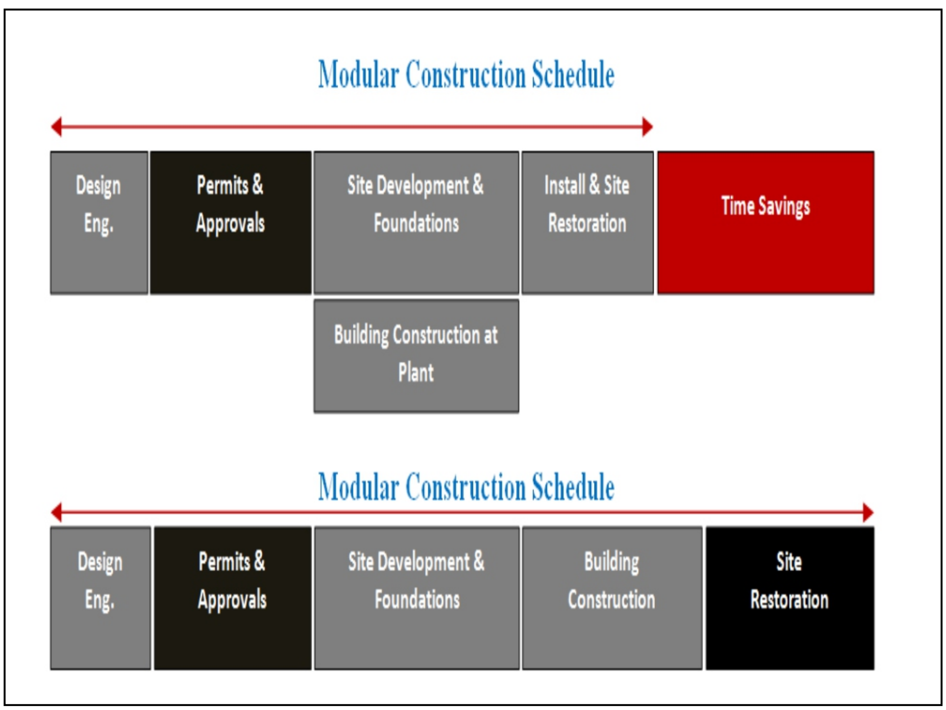

Figure 5: Modular construction v/s on-site Built construction schedule [2]

4.0 MAJOR TRENDS

Share of permanent modular buildings are approximately 42 percent of the total modular construction industry's $5 billion in annual revenues in North America (leasing and sales of relocatable buildings account for the remainder), [2]. For 2010, these companies reported revenue from the following top markets. Permanent modular buildings are considered real property, built to the same building codes and requirements as site-built structures, and are depreciated in a similar manner. As such, the markets for permanent modular construction are similar to the markets for site-built contractors, with few exceptions.

As per the Modular Building Institute (MBI) report on commercial modular construction in 2009, the major market served by PMC or modular construction is shown in Figure 6.

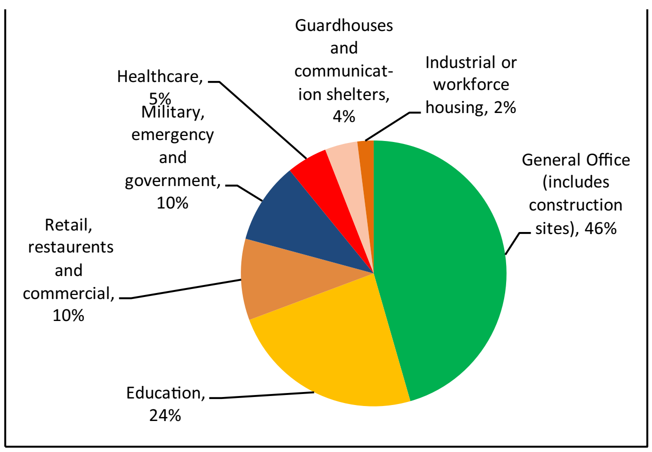

Figure 6: Market served by modular construction in commercial field, Source [6]

5.0 PMC IN INDIA

Prefabrication in India began with the emergence of Hindustan Housing factory (1950) under the cooperation of first Prime Minister of India, as a solution to the housing crisis resulted from the influx of refugees from West Pakistan in 1950s. But, now urbanization results rapid migration of the peoples in search of employment to cities. In PMC use of wood, steel, or concrete & fly ash can be applied, considering fly ash in concrete increases its workability and enhances thermal performance, additionally fly ash concrete blocks replaced the traditional clay blocks because they does not contains expansive soil cause walls and floors to crack with fluxes of temperature and humidity.

India's construction sector is running at Rs.4000 billion and government spending, private investments as well as foreign direct investment, has made India number one of the top ten spending nations on construction in the world. India is the second largest producer of cement after China with more that 250 million tons of cement.

A recent report named "Global Construction 2020", estimates that India will be the third largest global construction market after China and USA, [7].

The Government of India is supposed to achieve 9.0% GDP growth during Eleventh Plan period. For the achievement of such a growth, adequate infrastructure is the most basic requirement, [9,10].The government is establishing a program for infrastructure investment through both public and private sectors. The major associations and councils which contributed a lot for the development of Construction Industry in India are NBCC (National Building Construction Corporation, CIDC (Construction Industry Development Council, BAI (Builders Association of India), NBO (National Building Organization) and BIS (Bureau of Indian Standards). Indian trend in Infrastructure investment is shown in *Figure 7.*

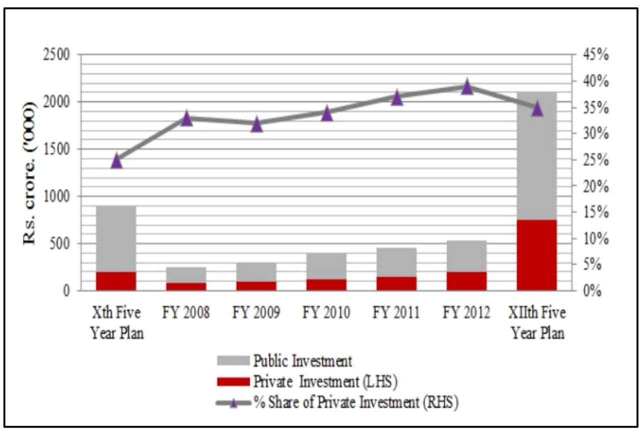

Figure 7: Indian trend in Infrastructure Investment, Source [Planning Commission, GOI]

The National Planning commission has estimated an allocation Rs.30 trillion to infrastructure sectors over the next five years. This includes construction of Highways, Airports, Bridges, Ports, Roads, Railways as well as water supply and sanitation amongst few of others. The 13thfive years plan estimated an investment of 10% of the national GDP into infrastructure which equates to equivalently Rs.60 trillion, [7,9].

On the other hand L&T installed a heavy engineering workshops at Powai (Mumbai), Hazira (Gujarat), Kansbahal (Odisha), Chennai,Vadodara (Gujarat), Kattupalli (Tamil Nadu) which have a combined fabrication area of about 1.2 sq.m with over 150,000MT capacity. L&T has already started a fully precast residential building of G+23 as a project in Parel, Mumbai in 2011. This project is supposed to provide total built up area of 1.2M sq. ft. 6 building towers. Construction of three out of six towers has completed in a record time of just 3 months. Speedy design and construction conforming to IS design codes and minimized labour intensive operations are the major objectives achieved by this project, [8].

The TATA housing group is also working on a housing project based on innovative prefabricated technologies. These houses will cost as low as approximately INR 32,000. Here, Tata Group will provide a kit having structural elements which can be erected or assembled in an efficient manner, houses having an area of 20-30 m2 and lifespan of 20 years. The project is still in pilot stage and will soon be implemented across the country, [8].

6.0 SUSTAINABILITY

A comprehensive, broader and inclusive definition of sustainability in construction is not just the process of buildings construction and the structures like houses, bridges, roads, ports, silos and factories in a "sustainable manner". Therefore, both the process and product must be seen in its backward forward linkages. As construction involves large investment and its impact on productivity, economy, financial and property markets, employment etc; therefore, is important. A complete process of construction occupies several things like, land and uses minerals, technology, water, chemical processes and energy in production of building materials and use. Therefore its impact on the environment must be considered.

It is widely accepted that the Permanent modular construction process is comparatively more resource efficient, not only in terms of the labor and money but also with regard to the material usage and wastage. The McGraw-Hill Smart Market Report indicated that 77% of architects, engineers and contractors surveyed reported a reduced generation at site,[2].The Environmental Protection Agency (EPA) reports that the average amount of waste generation of construction and demolition for a non residential projectis 21.19 kg/sqm, [2]. For a 929 square meter facility, this amounts to more than 20 tons of waste. If owners are capable to reduce this amount by just 5% using modular construction techniques that translates into 1.0 ton of wastage, per project diverted from the landfill, [2].The projects, under application of modular construction also have the ability to reduce waste in another manner. Due to the fact that these buildings are designed and constructed to be assembled on site, they are also therefore “designed for disassembly” or “design for deconstruction (DfD).”

Leadership in Energy and Environmental Design (LEED) rewards project stakeholders for appreciating where the water comes from, how we use and recycle it while found it on site and where it goes after construction end. By using integrated design, sustainable site category in LEED and Water Efficiency both are found in relation with each other.

In PMC or modular construction, utilizing an Innovative Waste Water Technology which allows fixtures that performs within the allowable water quantities listed in the Energy Conservation Act, 1992. Water Efficiency (WE), upto20-50% can be achieved through modular building manufacturing, [6].

In short, it is much easier to disassemble any modular project and salvage or reuse significant components of the building as compared to a similar on site built facility.

7.0 CONCLUSION

The concept and process of PMC is well known above and it is understood that this method of construction has diverse effect on economy, sustainability and time management of the project as compared to the site construction. Also, here we have gone through the various advantages and permanent modular construction by the data collected from various sources. As a result for involving PMC process, the comparison showed there is enormous difference in cost investments between the methods, which the prefab is very high when compared to conventional on this type of individual houses. The main advantages for prefab construction (PMC) is that, this also helpful when there is labor shortage. This is main drawback for prefab construction which is not economical to construct in this case.

Comparatively traditional methods of prefabrication of building elements found certain drawbacks. Availability of wide roadway, height below underpasses and bridges and pavement strength limits the transportation scope of the materials built at the factory. Traffic in highly urban cities does exponentially delay the projects. Temporary bracings during, lifting equipment, transportation and specialized framing to support prefabricated elements/modules on site are extra costs incurred.

A very high degree of planning, accuracy, precision, and coordination are required while assembling prefabricated modules on site. Any error in design of mass production may lead to a serious risk and existence of a defect would be replicated on a large scale.

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Importance of Hydraulic Modelling in the Development of Mega Container Terminal in WideMacro Tide Dominated Estuarine Harbour

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ABSTRACT

Among many developing countries in the world, India is also developing its infrastructures, especially waterfront facilities like berths, jetties and docks. Mumbai being epicenter of India's trade and commerce, two ports viz. Mumbai and Jawaharlal Nehru port (JN) are developing mega waterfront facilities to cater for berthing of modern ultra large container carriers. Mumbai Port being on leeside of Salsette Island and JN Port being well inside, tidal phenomenon of macro semidiurnal type (range 5 m) is more dominant than waves and is the governing factor in the design of waterfront facilities. JN port is developing a 2 km long mega container terminal and for fixing its location and orienta requires thorough knowledge of complex hydrodynamics of the region. The layout of terminal was finalized by conducting hydraulic model studies using a well calibrated physical model for Mumbai region with Scale of 1:400 (H) and 1:80 (V).

The studies carried out reveal that during flood phase of tide, flow field is parallel to the berth at northern end, while due to bifurcation of flow at Southern end of terminal undesirable strong tidal currents at a deviation of 180 approaches the terminal face aligned at 420 N. However, during ebb phase, scenario is reversed. Presence of solid approach bund at landing jetty near northern end of terminal forms undesirable eddies, while at southern end (2km), flow direction is safe for berthing. Study of flow field provides valuable information to modeler in nullifying the adverse effect at both the ends of terminal during flood/ebb. The replacement of bund at landing jetty by trestle on piles, while to guide the flow at the Southern end of terminal during flood, extension of reclamation bund by 200m on leeside of terminal achieves the desired flow conditions all along 2 km long berthing face of the mega terminal. Also, the gap between reclamation bund and berth face should be minimum to avoid formation ofsecondary currents at berth. Thus hydraulic modeling technique was utilised effectively to evolve optimum layout and alignment of mega terminal from hydrodynamic considerations.

Keywords : Estuary, Hydraulic model, Macro tide, Mega Terminal

1. INTRODUCTION

Many countries in the world in the past two decades have increased their foreign trade at an exponential rate due to rapid modernisation in the transportation facilities owing to significant development in the communication sector. Now-a-days goods/commodities and passengers in various countries can reach to any corner of the world in short period of time than ever before. This change is result of strong competition in transportation sector as well as availability of allied facilities like internet booking/banking. Among the various modes of transports such as road, rail, etc. waterborne transport is the cheapest mode of transport and most of the exchange of goods in the world is carried out through sea routes. In order to meet ever increasing demand of trade in the 21st century, there is a considerable scope to enhance waterborne transport activity in the world. The future developments in waterborne transport sector will be mainly in the form of building various infrastructures such as jetties, berths, terminals as well as building of Fast Ocean going ultra large container carriers. This development is possible due to availability of information on environmental and oceanographic parameters and thus sound knowledge about dynamic behaviour of ocean and modern techniques to simulate complex phenomena. In order to boost trade and tourism activity in various developing countries and consequently to cope with its requirement, various infrastructures are developing at an astonishing rate. India is a developing country and is expanding its facilities at an amazing rate to keep its pace with other Asian countries like China, Malaysia, Korea, etc. As a result many infrastructures in the form of road/rail networks, power plants as well as waterfront facilities like berths, jetties, docks, etc are being built. In order to explore marine resources and waterborne transport needs of future, Govt. of India has adopted a policy of liberalisation. As such governmental/non-governmental Agencies are developing many waterfront structures especially the mega terminals. These facilities are being built to cater the handling of modern ultra large ships, which will be the mode of transport in future. The major ports of India are owned by Government and development of mega waterfront structure on BOT basis is now-a-days a common practice in India. Since several decades Mumbai being traditionally the epicenter of India's trade and commerce, the road/rail and air connectivity with rest of world is well established. The ports of Mumbai and Jawaharlal Nehru (JN) are the sea ports. These ports situated in Thane estuary as shown in Figure1are presently serving the demand of traffic and have access to Indian Ocean through the Arabian Sea.

Figure 1 Location of Mumbai and Jawaharlal Nehru Ports in Thane estuary

In view of ultra wide entrance from Arabian Sea and availability of large water area in Thane estuary, new waterfront terminals to meet the future demand of traffic are under development. Both the ports are developing mega container terminals. These new mega waterfront terminals will further boost the economy of the country at much cheaper cost due to availability of excellent road, rail connectivity. One of such mega container terminal having berthing face of 2 km in a stretch in complex region of JN harbour is studied with the help of hydraulic model. The location and alignment of long mega container terminal is finalised based on the studies. The effect of adjacent structures on the flow field viz. eddy at the proposed mega terminal and remedial measures essential to nullify its effect as well as necessity of extending reclamation bund on leeside of container terminal to achieve desirable flow indicates the importance of hydraulic modeling in the development of mega container terminal.

2. PRESENT WATERFRONT FACILITIES AND SCENARIO OF FLOW COMPLEXITY

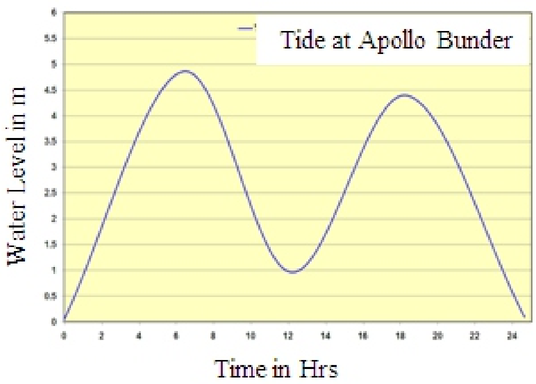
The JN port is a major container port of India and is presently having about 2 Km long waterfront facility to handle container traffic and shallow water berths. These facilities are operated by various Agencies while liquid berth is operated by BPCL. The layout of JN port with various facilities is shown in Figure 2. The navigational channel is maintained to a depth of about 12m for past few decades and is serving the safe movement of ships entering/leaving the port.

Figure 2 View of existing berthing facilities at Jawaharlal Nehru Port

The layout of various berthing facilities in JN port were finalised after conducting extensive field studies in Thane estuary along with rigorous physical/numerical hydrodynamic modeling of the region. The information about various oceanographic parameters such as tides, waves, siltation pattern etc. over the decades available was useful in finalizing alignment of various waterfront structures. In view of Mumbai port is on the leeside of Salsette Island and JN port being far inside from wide entrance of Thane creek, wave tranquility was not the major criteria in evolving design of existing waterfront structures. However, entrance to these harbours from Arabian sea being very wide (10 km) and water area extends 30-40 km north inside the estuary with the presence of macro tides (tidal range of 5.0m) of semi-diurnal nature, it results in exchange of significant tidal flux during flood/ebb phase of tide. As such strong tidal currents of 1 -2 m/sec exist in the harbour area. Also presence of many islands, deep navigational channels, rocky outcrops, shallow regions and existence of many mudflats like Uran, Sewari etc. alters the flow field significantly during various phases of tides. The type of material in suspension is of cohesive nature; therefore siltation is primarily governed due to settlement of suspended sediment. Hence finalising the location as well as alignment of any waterfront facility in this region is governed not only by tidal flow field viz. currents (strength/ direction) but also due to siltation. The field investigation and hydraulic modeling is essential for simulation of complex flow field and to assess effect of reclamations on surrounding area while fixing the location and alignment of new waterfront facilities.

3. FIELD DATA ON OCEANOGRAPHIC PARAMETERS

The field data collected on oceanographic parameters such as tides and current at proposed development in JN Port area was used to simulate flow condition in the model. The measured field data on tide at Apollo Bundar as well as current in front of north end of mega container terminal is shown in Figure-3(A) and (B) respectively and was used to simulate the hydrodynamic condition in the model to study the flow pattern at proposed location of container terminal.



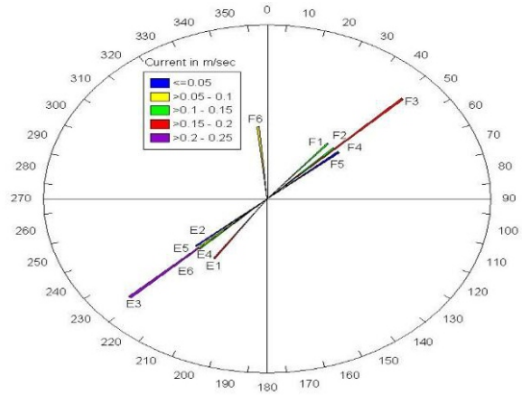


Figure 3(A) Tide during Spring condition **Figure3(B)**Current near north end of Terminal

4. DEVELOPMENT OF MEGA CONTAINER TERMINAL - SELECTION OF LOCATION

The JN port considering the future demand of trade, proposes to handle ultra large container carrier. It has been proposed to develop a mega container terminal having a berth length of 2 km with 200 Ha of reclamation on its leeside for stacking the containers. In order to explore its operability to fullest extent, proposal of widening and deepening of main navigational channel up to 16m with respect to Chart Datum (CD) is under consideration. The complexity of tidal flow condition approaching JN port is that flow during flood tide gets bifurcated towards Pirpau channel and Elephanta deep due to presence of Elephanta Island, While rest of the flow floods the wide Uran mud flat region as shown in Figure 4. During ebb tide flow reverses and channel in Elephanta deep being deeper than surrounding, majority of the flow coming from Thane and Panvel estuary passes through JN navigational channel wherein current strength is about 1-2 m/sec. This flow afterwards meets the flow from Pirpau, while flow from Uran mudflat area also joins it at the south of Jawahar Dweep. In view of present terminals being aligned parallel to JN navigational channel, existence of shallow depth of 3-4 m on the north of Nhava creek and environmental restrictions to have new terminal towards Gharapuri Caves (Elephanta side), the area which remains available for future development is only at the south of existing BPCL berth. As such the location of proposed 2 km long mega terminal is considered on the south of BPCL berth. Considering various factors such as smooth operability all along 2 km berth face irrespective of phase of tide, safety from wave disturbance during monsoon season for waves approaching from west and south-west, minimal effect of huge reclamations on existing nearby waterfront facilities, considerable increase in future traffic of ultra large container carriers in JN navigational channel, it is inevitable to plan the location of new terminal well inside inline of existing berth faces. Hence considering the above parameters, conceptual layout of proposed terminal evolved is shown in Figure 4. The 2 km long mega container terminal in line with existing BPCL berth requires provision of gap of about 350 m as the BPCL berth is also to be kept operational on both sides. However this layout happens to have southern end of mega terminal very close to Karanja Naval basin, dredging of huge area in front of mega terminal and leeside of reclamation bund found to be crossing the port limit. Also significant gap between reclamation face and berth terminal will create formation of secondary currents during flood phase of tide and undesirable current pattern near the terminal as the flow will approach the berth at an angle. While during ebb phase, flow from Elephanta deep channel and Uran mud flats crosses at southernmost end of terminal, thereby it will result in undesirable effects during berthing/de-berthing.

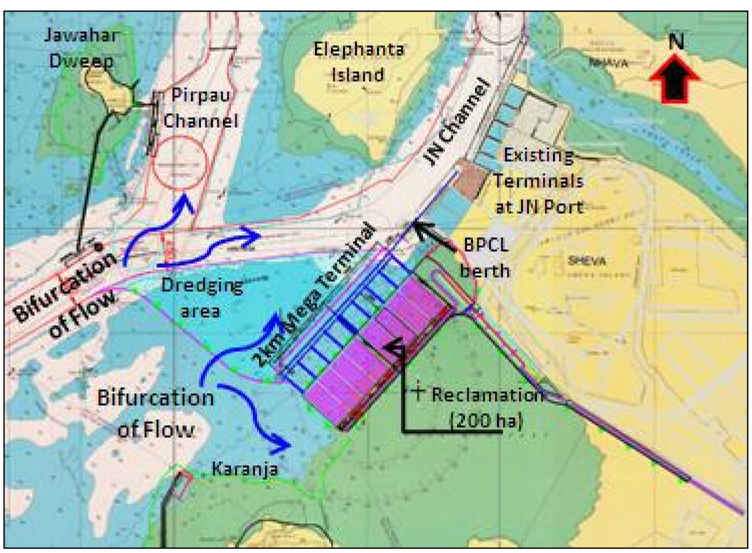


Figure 4 Location of Mega container terminal south of existing BPCL and reclamation on leeside

Considering the complexities which will arise for above mentioned layout, it is desirable to shift the berth towards reclamation bund with shape of reclamation as triangular to avoid crossing of port limit as well as other hydrodynamic considerations.

5. LAYOUT OF MEGA TERMINAL PROPOSED FOR HYDRAULIC STUDIES

Considering the limitations of earlier mentioned layout the location of 2 km long mega terminal was modified for assessing its suitability from hydrodynamic consideration and is given in Figure 5. Based on the field data on current, the alignment of container terminal is considered as 42° N and minimal gap of about 100 m is kept between berth face and the face of the reclamation bund to guide the flow at berth face and avoid formation of secondary currents. Also an area of about 200 Ha in a triangular shape to minimise adverse effect on flow pattern was considered for stacking of containers. The berth pocket is proposed to be deepened to 16.5 m blow CD, while remaining area in front of the proposed terminal will be deepened to 13.1 m in such a way that it will guide the flow along the berth. However assessing the suitability of layout proposed from safe operational considerations, it is essential to study the flow field using hydraulic model.

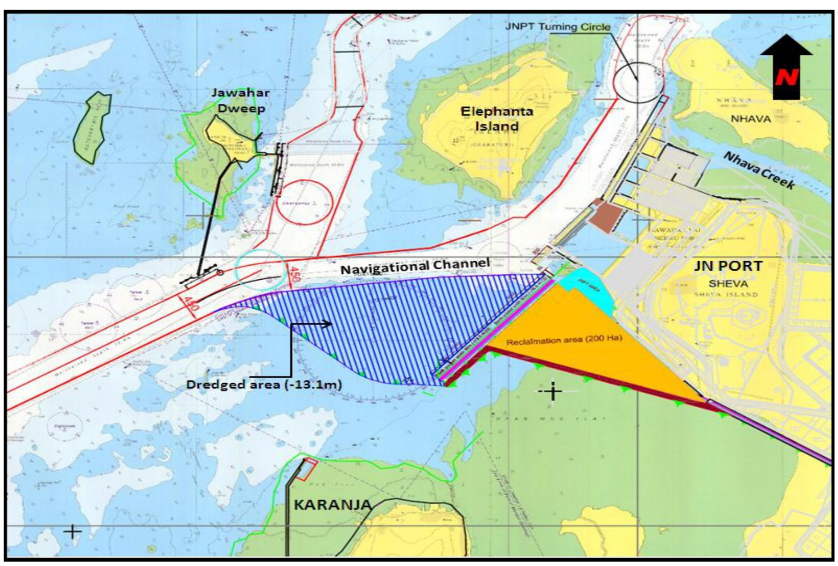


Figure 5 Layout of 2 km Long Mega Container Terminal with Triangular Shape of Reclamation

The formation of complex flow phenomena near berth face such as dynamic eddy, separation of non-uniform unsteady flow, determination of siltation prone zones, effect of marine infrastructures such as reclamations on the surroundings etc. can be better understood through flow visualisation and its measurements using physical model. The physical model based on scale laws presents the nature in miniature and hence useful in taking the decision for finalising the layout of mega terminals.

5.1 Modeling Principles

The purpose of scale modeling is to study any physical system by use of another at a smaller or larger physical scale but with the variables adjusted so that all forces, motions in the two physical systems are in the same proportion and the physics of the physical system remains unchanged. Hydraulic scale modeling techniques based on the similitude principles is used to solve various problems in hydraulic engineering such as; coastal and ocean engineering. For the hydraulic modeling a distorted tidal model was used to study hydraulic parameters in finalizing the layout of proposed 2 km. long container terminal. As the gravity and inertia forces are the two dominant forces in tidal flow; distorted tidal model works on the principles of Froude Similitude. The expression for Froude number (Hudson RY et al. 1979) is as follows.

$$, = \overline{\qquad\qquad}$$

$$= \frac{\ \ ^{2}\ ^{2}}{\ \ _{3}} = \frac{\ ^{2}}{} \qquad (1)$$

As per Froude's similitude, = ; Hence, the velocity scale ( ) and Time Scale T_r are:

$$V_r = d_r^{0.5} \qquad (2)$$

$$T_r = \frac{L_r}{d_r^{0.5}} \qquad (3)$$

5.2 Description of Physical Model and Generation of Tide

CWPRS a premier hydraulic institute of India has played a pivotal role in the field of coastal engineering to finalize the layouts of major ports, navigational channel and alignment of jetty/berths, etc over past several decades. The Mumbai Port model at CWPRS is a permanent physical model and it covers portions of Thane, Panvel Dharamtar estuary as well as part portion of Arabian Sea. The tidal model of Mumbai Port is a distorted model having horizontal scale 1:400 and vertical scale 1:80. The total model area is about 150 m X 90 m and it is a rigid bed model. The water supply to the model is through three pumps of 75 HP each with total discharging capacity of about 1500 lit/sec. the water supply system is of recirculation type. The model is covered by a shed of size 70 m X 45 m, representing an area of about 28 km. X 18 km. in proto. The covered portion includes main area of interest i.e. Mumbai and Jawaharlal Nehru harbor areas, Karanja etc. The Mumbai Port model is well equipped with an Automatic Tide Generating (ATG) system which can generate pseudo tides of required amplitude and period. Due to the presence of semi-diurnal tide in the Mumbai harbor, a typical tidal cycle of 12 hrs. 25 minutes (proto) is reproduced in about 17 minutes by using the time scale of 1 sec : 44.72 sec. Hence, the duration of a typical flood/ebb cycle is 8 minutes and 30 sec. The generation of pseudo tide is controlled by the ATG system. The model is fitted with balanced radial gates resting on weirs and is connected to a common shaft. The common shaft is connected to a gear box, which is driven by a stepper motor. The movement of stepper motor is controlled by motor drive, which is in turn connected to the computer. The computer is fed with the required water level, while the actual water level in the model is supplied by a pressure transducer known as rose mount sensor. At every time step, the computer compares the actual water level with required level in the model. By controlling the water levels over the weir, tides are generated in the model. The pictorial representation of Mumbai harbour area and ATG system are shown in Figures 6(a) and 6(b) respectively.

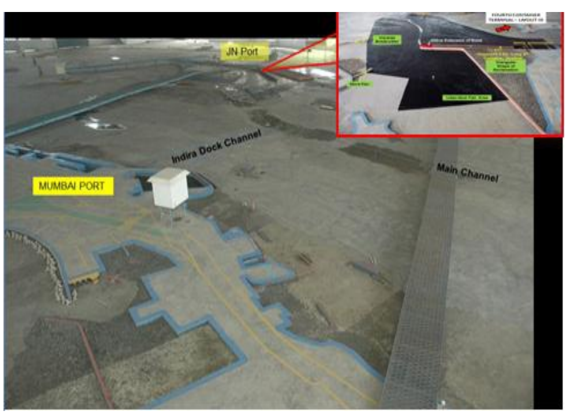
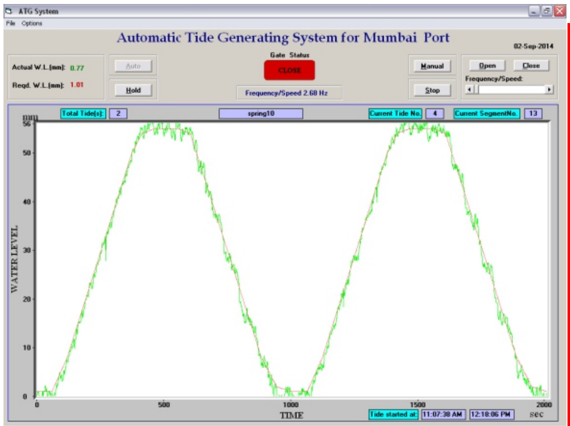


Figure 6(a) Pictorial View of Mumbai Model

Figure 6(b) Automatic Tide Generating system

5.3 Calibration of Model and Hydraulic Model Study

A tidal model is said to be calibrated when the flow conditions in model are in proportion to that in prototype and this is possible by comparing water levels and current (magnitude/direction) in model with prototype. The model was calibrated by generating a tide as shown in Figure 7(a) for a tidal data measured and comparison of typical pseudo tide during spring is shown in Figure 7(b). The velocity measurements were also carried out by digital image processing technique. In this technique, paper confetti is spread on the water surface and it moves with the flow velocity. Photographs of the flow are taken at fixed duration, for a known exposure time, by using digital camera. The displacement of confetti in known time gives magnitude of velocity at surface while its direction can be found with respect to North. Having information about water depth at different time interval, the velocity at mid depth is computed. The tide measured in model have 95-98% agreement with prototype tide and in view of model being laid with latest bathymetry, velocity field has also been found to be in good agreement. The hydraulic model studies were initially carried out to assess the flow conditions all along 2 km long container berth for prevailing hydrodynamic conditions. The studies indicate that during flood phase of tide, at the northern end and central portion of proposed terminal, flow remains almost parallel to the berth. The deviation of flood currents with the alignment of mega container terminal at 42^o N was 3^0-4^o and is within permissible limit. However, due to the bifurcation of strong tidal currents towards Uran mudflat from deep navigational channel; during first three hours of floo d tide, flow approaches the southern end of terminal at an angle of 60-75^0N indicating that deviation is about 18^0-33^0 with mega terminal at 42^0 N. This deviation of flow with terminal face is undesirable.



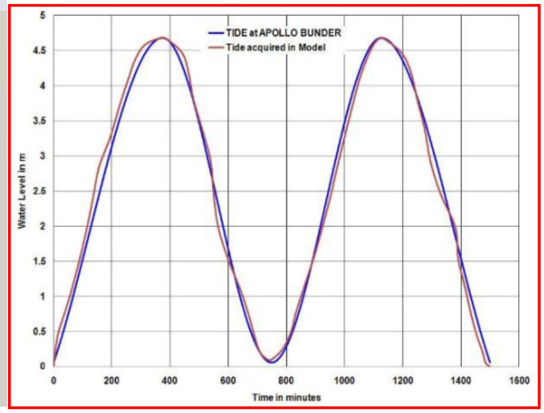
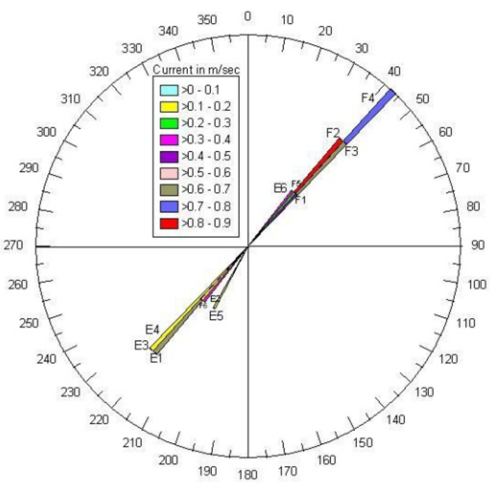


Figure 7(a) Tide Generated at Mumbai model **Figure7(b)** Comparison of proto and model tide

The tidal currents measured in model at north and south end of terminal are shown in Figures 8(a) & 8(b). Whereas, the flow field during ebb phase of tide indicates that during first two hours of ebb tide at the northern end of terminal eddies are getting formed and with the passage of ebb tide, it gets shifted towards the central portion of the proposed terminal. It indicates that presence of solid approach bund north of northern end of terminal shown in Figure 9(a) creates undesirable formation



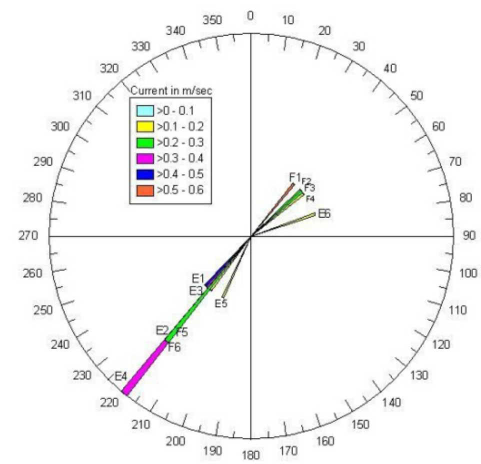
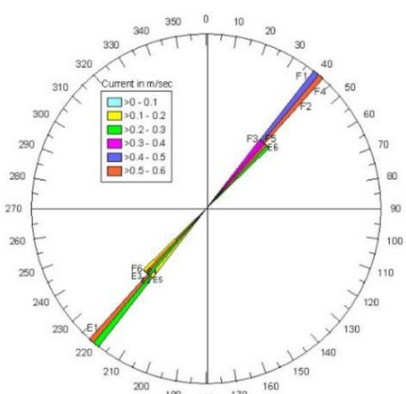


Figure 8(a) Current at Northern end of Terminal **Figure8(b)** Current at Southern end of Terminal

Figure 9(a) Eddy at north end due to solid Bund **Figure9(b)** Eddy disappeared due to pile Trestle

of eddies. The replacement of solid bund providing approach to landing by trestle on piles improves the flow conditions and eddies are seen to be disappeared as shown in Figure 9(b) In a similar fashion in order to improve flow conditions at the southern end of terminal during flood phase of tide, it is essential to align the flow towards berth face and in order to achieve this, extension of reclamation guide bund beyond 2 km length of terminal was studied with different extensions of 100, 200 and 300m. The studies conducted reveal that, extension of guide bund by 200m is sufficient to achieve desirable flow conditions at the southern end of terminal. The current measurements taken at north and south end of terminal with approach to landing jetty on piles & extension of bund by 200 m beyond 2 km long terminal are shown in Figures 10(a) and 10 (b) and layout is considered as final.



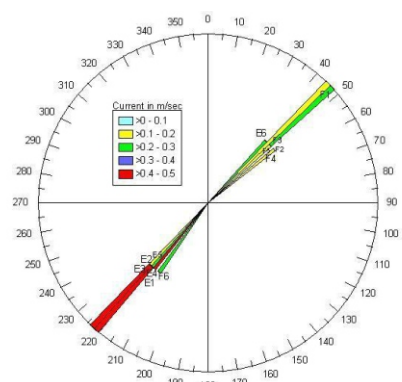


Figure 10(a) Current at north end -Final Layout **Figure 10(b)** Current at south end-Final Layout

The studies carried out with these two modifications indicate that, flow field all along the 2 km long proposed terminal has been improved and berth can be operated safely irrespective of phase of tide.

6. CONCLUSIONS

Based on hydraulic model studies carried out, the following broad conclusions can be drawn, which also highlights the importance of hydraulic modeling in assessing flow complexities and remedial measures required to achieve desired flow conditions all along 2 km long mega container terminal in tide dominated wide estuarine region:

- Physical model provides admirable information on flow field by visualisation (formation of eddy) during flood/ebb tide as well as velocity field to guide the remedial measures to be taken for achieving desired flow field all along berth face of mega terminal in complex hydrodynamic conditions to finalise the layout and alignment of the terminal.
- The replacement of solid approach bund near landing jetty north of mega container terminal with the trestle on piles and extension of reclamation bund by 200 m at south end of terminal has helped in achieving desirable flow all along 2 km berth face irrespective of phase of tide.
- The berth face should be aligned at 42^0 N and a gap of 100 m should be provided between berth face and the reclamation bund to avoid formation of secondary currents at berth.

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Axial Vibration Of A Cantilever Beam With A Tip Mass

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ABSTRACT

In this study free axial vibration of a cantilever beam with a tip mass is analyzed. The boundary conditions are written for the fixed end and the end with the tip mass after the differential equation of motion issolved by separation of variables method. The frequency values for the first three vibration modes of the beam are obtained for various values of concentrated mass and presented in the tables. The frequency values for the concentrated mass values of zero are also compared with the ones of cantilever beam without tip mass and nearly the exact values are obtained with negligible error percentages.

Keywords: Axial vibration, Cantilever Beam, Tip Mass, Frequency

1. INTRODUCTION

In practice, the representation of a beam by a discrete model is an idealized model; however, in fact, beams have continuously distributed mass and elasticity. Mostly, especially for the axially vibration, beams are modeled as continuous systems having infinite number of degreed of freedom [1-10].

In this study, the free vibration analysis of a uniform axially vibrating cantilever beam with a tip mass is made. The differential equation of motion of the axially vibrating beam is solved by separation of variables method [11] and the displacement function is obtained. The boundary conditions are written for the fixed end and the tip mass. The natural frequencies for the first three modes are obtained for the various values of the tip mass. The results obtained for the tip mass value of zero are compared with the frequency values of the cantilever beam without a tip mass. The axially vibrating beam considered in the study is assumed to be homogeneous and isotropic.

2. SOLUTION OF EQUATION OF MOTION FOR AN AXIALLY VIBRATING BEAM

An axially vibrating beam, given in Figure.1, with the distributed mass m, the length L, the modulus of elasticity E, the cross-section area A and the axial rigidity AE has a dimensional differential equation of motion for free vibration as [12]

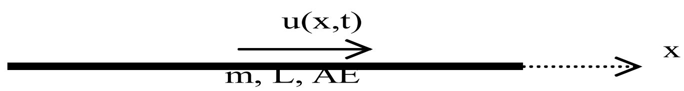

Figure 1: An Axially Vibrating Beam

$$\frac{\partial^2 u(x,t)}{\partial x^2} - \frac{m}{AE}\frac{\partial^2 u\, x,t}{\partial t^2} = 0$$

(1)

where u(x,t) is the displacement function of the beam in terms of both displacement x and time t. Application of the separation of variables method to Eq. (1) as in the form of Eq. (2) is commonly used in vibration analysis of beams.

$$(\ ,\ ) = \quad . \quad = \quad .[\ .\sin \quad + \ .\cos \quad]$$

(2)

In Eq. (2), X(x) is the eigenfunction named as shape function, T(
eigenvalue of the solution named as natural frequency and A, B are constants.

The derivatives used in Eq. (1) can, therefore, be written as

$$\frac{\partial^2 u\, x,t}{\partial x^2} = u''\, x,t = X''\, x\, .\, A.\sin \omega t + B.\cos \omega t = X''\, x\, .\, T\, t$$

(3)

$$\frac{\partial^2 u\, x,t}{\partial t^2} = u\, x,t = X\, x\, .\, (-\omega^2)\, A.\sin \omega t + B.\cos \omega t = -\omega^2 .\, X\, x\, .\, T\, t$$

(4)

where ($^{//}$) and ($\ddot{}$) denote the second order derivative due to x and t, respectively. Substitution of Eq. (3) and Eq. (4) in Eq. (1) gives the governing equation of motion in the form as

$$X'' \; x \,.T \; t \; + \frac{m\omega^2}{AE} X \; x \,.T \; t \; = 0 \quad X'' \; x \; + \frac{m\omega^2}{AE} X \; x \; = 0 \quad 0 \le x \le L$$

(5)

$$\text{for } \alpha^2 = \frac{m\,\omega^2}{AE} \qquad X'' \, x + \alpha^2 X \, x = 0$$

(6)

The characteristic equation and the solution of Eq. (6) is given as follows as D being d/dz:

$$2 + \; 2 = 0 \;\rightarrow\; {}_{1,2} = \pm \qquad (7)$$

$$(\;) = \;{}_{1}.\sin \; + \;{}_{2}.\cos \qquad (8)$$

Eq. (8) gives the shape function of the axially vibrating beam due to the displacement variable, x. Therefore, from Eq. (2), the displacement function of the axially vibrating beam has the form of Eq. (9).

$$, \;=\; . \;=\; {}_{1}. \; + \; {}_{2}. \; .(\;) \quad (9)$$

3.0 BOUNDARY CONDITIONS

Figure 2: Axially Vibrating a Cantilever Beam with a Tip Mas

Two boundary conditions have to be written for the cantilever beam with a tip mass in Figure.2 since two integration constants (C_1, C_2) are obtained in the solution of second order differential equation of motion. The boundary conditions written for the left and the right ends of axially vibrating beam are given, respectively, as [13] for x=0 = 0, = 0 (10)

for x=L = , = ′ = , = − . (= ,) (11)

where M is the tip mass value and N(x,t) is the axial force. If Eq. (9) and its derivative are substituted into Eq. (10) and Eq. (11) one gets the following relation between the coefficient matrix and the integration constants.

$$k \; . \; C = 0; \quad \propto.\cos\propto L \; -\propto^2 ._{M}\sin(\propto L) \,.\, C_1 = 0$$

(12)

$$k = \propto.\cos\propto L \; -\propto^2 .\sin(\propto L) = 0$$

(13)

where $\propto^2 = \frac{M.\omega^2}{AE}$ $_m$. For non-trivial solution equating the determinant of the coefficient matrix

of Eq. (12) to zero, as in Eq. (13), will give the eigenfrequencies of the axially vibrating cantilever beam with a tip mass. These frequencies are computed by a program written by the author considering the secant method [14].

4. NUMERICAL ANALYSIS

The first three natural frequencies of the axially vibrating cantilever beam with a tip mass are calculated for M values of 0, 10^{-10}, 10^{-9}, 10^{-8}, 10^{-6}, 10^{-4}, 10^{-2}, 10^{-1}, 10^{0}, 10^{1} and 10^{2}, the beam length of L=1 m. and the modulus of elasticity of E=2100000 kg/cm^2. IPB-100, IPB-300 and IPB-600 profiles are used for numerical analysis with the mechanical properties given in Table 1 where h is height, G is weight per length, A is cross-section area and AE is axial rigidity of the corresponding profile. The distributed mass of the beam m is calculated from G/g as g being the acceleration of gravity with the value of 981 cm/sn^2.

Table 1: The Mechanical Properties of the Profiles Used in This Study

Profile	h (cm)	G (kg/cm)	A (cm^2)	AE (kg)
IPB100	10	0.081	10.3	21630000
IPB300	30	0.422	53.8	112980000
IPB600	60	1.22	156	327600000

The frequency values computed due to different values of the tip mass are presented in Table 2, Table 3 and Table 4 for, respectively, IPB-100, IPB-300 and IPB-600. The frequency values obtained for M=0 are compared with the exact frequency values obtained from the frequency equation of cantilever beam without a tip mass in the first row.

Table 2: Frequencies Computed for Different Values of the Tip Mass for IPB-100

		1	2	3
Exact Frequencies for Cantilever Beam	=	8039.7053	24119.1160	40198.5266
M	**0**	8039.7053	24119.1160	40198.5266
	10^{-10}	8039.7052	24119.1157	40198.5261
	10^{-9}	8039.7044	24119.1131	40198.5218
	10^{-8}	8039.6956	24119.0868	40198.4779
	10^{-6}	8039	24117	40194
	10^{-4}	7944	23831	39719
	10^{-2}	4099	17306	32815
	10^{-1}	1451	16213	32226

	10^{0}	465	16093	32166
	10^{1}	148	16081	32160
	10^{2}	47	16080	32159

Table 3: Frequencies Computed for Different Values of the Tip Mass for IPB-300

		1	2	3
Exact Frequencies for Cantilever Beam	=	8050.0567	24150.1702	40250.2836
M	**0**	8050.0567	24150.1702	40250.2836
	10^{-10}	8050.0567	24150.1701	40250.2835
	10^{-9}	8050.0565	24150.1696	40250.2827
	10^{-8}	8050.0549	24150.1646	40250.2743
	10^{-6}	8050	24150	40250
	10^{-4}	8032	24095	40157
	10^{-2}	6567	20333	35076
	10^{-1}	3139	16770	32547
	10^{0}	1056	16170	32236
	10^{1}	336	16108	32204
	10^{2}	107	16770	32201

Table 4: Frequencies Computed for Different Values of the Tip Mass for IPB-600

		1	2	3
Exact Frequencies for Cantilever Beam	=	8062.0672	24186.2015	40310.3358
M	**0**	8062.0672	24186.2015	40310.3358
	10^{-10}	8062.0672	24186.2015	40310.3358
	10^{-9}	8062.0671	24186.2013	40310.3355
	10^{-8}	8062.0665	24186.1996	40310.3329
	10^{-6}	8062	24186	40310
	10^{-4}	8056	24167	40278
	10^{-2}	7465	22451	37580
	10^{-1}	4769	17884	33223
	10^{0}	1774	16325	32350
	10^{1}	572	16145	32259
	10^{2}	181	16127	32250

5. CONCLUSIONS

In this study free axial vibration of a cantilever beam with a tip mass is made. The natural frequency values are obtained for different values of the tip mass and presented in tables. It can be seen from Tables 2, 3 and 4 that as the tip mass values increase from zero through a value of 10^{-6} for all profiles considered in this study the frequency values gently decrease, however, after the mentioned values the frequency values begin to decrease dramatically and rapidly. Increasing the height of the beam section causes an increase in frequency values.

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