Evacuation Process and Outcome Predictions from the Perspective of Emergency Management

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INTRODUCTION

The core objective of an emergency management plan is to ensure that effective, efficient and safe evacuation is achieved in the event of a real life emergency.

The success of evacuations significantly relies on planning and preparedness. There are two aspects of emergency evacuation planning which requires careful consideration: assumed sequence of events during an emergency and the actual sequence of events. The objective is to align the assumed and actual sequences as much as possible.

With a conventional approach, emergency evacuation (or response) planning is based on various guidelines and standards which require no or only a limited amount of pre-evacuation quantification. The plans are based on the assumption that a building with a code compliant egress design (prescriptive or performance based) will provide the necessary environment for successful emergency evacuations. The plans concentrate on parameters such as emergency control team structures, warning systems and messages, directional signage, mustering points and emergency preparedness training. The plan is periodically evaluated by means of drills. Especially in buildings with large occupant numbers, the drills are limited in scope and scale and they fall short of giving a reliable indication of likely outcomes of a full scale evacuation.

While it is not a requirement of codes and regulations, it is a proven fact that emergency evacuation plans benefit significantly from quantitative assessments conducted in support of the core assumptions. The assessments can be conducted as “desk top” or “computer modelling” exercises and in some cases a combination of both. The key aim of the assessment is to evaluate and where possible, quantify the pre-evacuation/evacuation/post-evacuation conditions. The assessment may either be limited to the evacuation process only or may also consider the impact of the actual incident on the evacuation.

Desk top assessments are effective tools for smaller scale buildings with limited occupant numbers. For large and complex buildings computer assessments become essential. Computer assessments of evacuations may also be referred to as “evacuation simulation modelling”. While there are multiple options available, it is the scale of the evacuation that will dictate the type of simulation software adopted.

The objective of this paper is to discuss methods and approaches that can be adopted to predict the process and outcome of evacuations from the perspective of emergency management. The paper provides examples of desk top and computer based assessments. Some real life examples of computer models for single building; precinct and large scale (i.e. town or city) evacuations are also provided.

The high rise building evacuation example provided discusses issues such as assembly/mustering area capacities, time required to fully evacuate a building and time required for occupants to return to their initial locations. The evacuation process is also discussed in the context of business continuity which is a key concern of many organisations with relation to emergency evacuations.

EMERGENCY EVACUATION/RESPONSE PLANS AND FIRE DRILLS

Emergency evacuation plans are developed to ensure the safest and most efficient evacuation time of all expected residents of a structure, city, or region.

According to the Singapore Civil Defence Force Guidelines [1] the purpose of the Emergency Response Plan is to ensure the safeguard of human lives in the event of fire, to establish a systematic and orderly evacuation plan, to ensure prompt raising of the fire alarm and marshalling of first aid fire-fighting efforts and to establish responsibilities of individuals involved in handling emergencies.

These purposes are in line with many others adopted by authorities around the globe. All codes and standards recommend emergency evacuation drills or exercises to improve the effectiveness of the plans. The primary reason for conducting fire drills is to educate building occupants about the procedures to follow in the event of an emergency that requires evacuation. Fire drills serve to educate building occupants, assist in the evaluation of emergency plans, and identify potential issues with the building's means of egress [2].

NFPA *101®, Life Safety Code* [3], contains specific requirements for fire drills in occupancies. The following excerpt explains the code's intent:

> *The purpose of emergency egress and relocation drills is to educate the participants in the fire safety features of the building, the egress facilities available, and the procedures to be followed. Speed in emptying buildings or relocating occupants, while desirable, is not the only objective. Prior to an evaluation of the performance of an emergency egress and relocation drill, an opportunity for instruction and practice should be provided. This educational opportunity should be presented in a nonthreatening manner, with consideration to the prior knowledge, age, and ability of audience.*

The Australian Standard AS3745-2010 "Planning for Emergencies in Facilities" [4] states that:

> *After emergency procedures have been written, evacuation exercises shall be conducted to ensure that the procedures are satisfactory. Once an organization has written and adopted emergency procedures and established that the emergency procedures are satisfactory and workable, a program of evacuation exercises should be established. These may be conducted either as partial evacuation exercises or a total exercise covering a building, structure and workplace. The aim of evacuation exercises is to have all occupants participate in at least one evacuation exercise per year consistent with the nature and risk of the building, structure and workplace.*

BS 9999:2008 "*Fire Safety Code of Practice for the Design, Management and Use of Buildings*" recommends a similar approach [5].

The basic objective of these code recommendations is: "*to be ready, when a real emergency evacuation is required*". This emphasises the importance of "*getting it right*" and adopting means to compensate for the aspects of emergency preparedness the codes may not be addressing. The missing aspect of codes and standards is the actual dynamics of the evacuation from the perspective people movement, based on the actual geometry of the building/precinct being evacuated, the effectiveness of the proposed egress paths and the number and characteristics of the people being evacuated. This is where quantitative assessments provide a powerful tool.

QUANTITATIVE ASSESSMENTS

Quantitative assessments can be conducted as "desk top" or "computer modelling" exercises. The key aim of the assessment, whether it is desktop or computer aided, is to evaluate and quantify the pre-evacuation/evacuation/post-evacuation conditions. The assessment may be limited to the evacuation process only but may also incorporate the impact of the emergency on the evacuation, such as tenability conditions on egress paths. The assessments will have different characteristics based on the scale of the evacuation, which can be categorised in three main groups:

i. single large building evacuations;
ii. multi-building / precinct evacuations; and
iii. very large scale (i.e. suburb/town/city) evacuations.

Regardless of their scale, evaluations must be carried out from the perspectives of:

- Initial occupant numbers, location and distribution
- Final destination location and capacity
- Movement paths and directions during the evacuation
- Travel patterns
- Travel speeds and times
- Factors controlling specific evacuations

The information provided by the quantitative assessments, among other things, must assist in predicting the actual time it will take to evacuate a building, problems that may be encountered during evacuations (i.e. bottlenecks and queuing), the effectiveness of the egress paths and the appropriateness of the final destination. It should be noted that even with the most advanced quantitative assessment methods the outcome is only indicative and not absolute. It is a function of the input data and the assumptions adopted. Hence, it will be essential that the outcomes are further evaluated and refined by persons with a good understanding of the evacuation process being assessed.

CHARACTERISTICS OF DIFFERENT SCALE EVACUATION ASSESSMENTS

Single Large Building Evacuation Assessments

Typical buildings under this category would include but not be limited to mega-malls, sports arenas, high-rise buildings, airports and exhibition/convention centres.

In the assessment the accuracy and appropriateness of the input data in relation to the building being analysed and its occupants is crucial to the outcome of the assessment. Such information will need to be obtained from different sources.

For the purposes of analysis the building layout and egress paths along with initial occupant numbers, location and distribution can be obtained from typical building plans. For buildings without fixed seating or pre-determined use, the numbers can be based on real occupant counts or more likely code prescribed numbers.

An aspect of controlled evacuation of buildings with emergency response plans which should be assessed is the final destination for occupants (i.e. assembly point or mustering areas) These areas are usually selected, established and designated based on their location, accessibility and "assumed" capacity. In order to ensure efficient evacuation the capacity should be estimated using pedestrian crowding studies. For example, based on research studies on crowd dynamics [6] 0.25 to 0.50 m^2 area of occupancy per person is the limit for comfortable assembly conditions for people. When the density falls below 0.25 m^2 extreme congestion may take place and movement may become impossible. In allocating assembly points such scientific information must be taken into consideration (Figure 1).

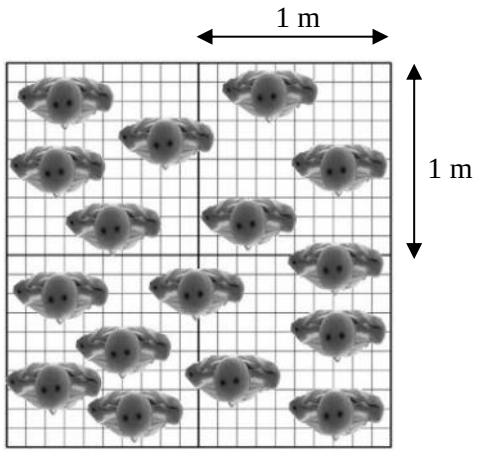


Figure.1 Visual representation of the occupant density of 0.25 m^2 per person [7]

Once the "initial occupant numbers and locations" and the "final destination location and capacities" are identified the next stage will be to evaluate the movement paths and directions. The egress/movement paths will need to be evaluated with respect to following factors:

1. **Accessibility**: Visual and physical accessibility of the paths.
2. **Egress Path Dimensions**: In relation average width and carrying capacity, the egress path must be wide enough to accommodate multiple columns of people walking abreast. The minimum width required for each column is approximately 750 mm [6], [8], [9]. It should be noted that egress widths dictate the flow rates and travel speeds. Disabled travel must also be taken into consideration.
3. **Bottlenecks**: Reduction in egress widths and merging of egress streams could result in bottlenecks. Bottlenecks would lead to queuing and delays in evacuation. Similarly obstructions on egress paths would result in sudden reduction in egress widths and also cause queuing and delays.
4. **Travel Distance**: The length of the egress path (or alternatively the travel distance) is another key factor which dictates the evacuation time.

5. **Obstructions and Counter Flows**: Evacuation through already occupied general pedestrian traffic areas could lead to obstructions and counter flows. Fire brigade intervention during evacuation also could lead to counter flow.

   Where large numbers evacuate simultaneously, group and crowd flow can also affect the travel patterns. At the perception stage, occupants detect other adjacent occupants and calculate the crowd density and the crowd flow direction. At the execution stage, when encountering cross flows in a dense crowd, occupants temporarily reset their navigation target from its original target to nearby group members (according to the separation distance and the member's influence). The figure below shows the patterns of groups in different crowd flow situations. Without any cross flow, the groups tend to walk as a cluster with formation in a V-shape or horizontally along the travelling direction. Lane-forming patterns emerge as groups are crossing each other in opposite direction (Figure 2).



Figure.2 Groups form clusters initially then form lanes

6. **Travel Speeds and Flow Rates**: Travel speeds and flow rates are highly critical parameters and they should be obtained from research studies on pedestrian movements by the likes of Fruin and Pauls [6], [8], [9]. (Figure 3).



Figure.3 The impact of crowd density on travel speed

Multi-Building/Precinct Evacuations

Multi-building evacuation assessments are adopted for the purposes of predicting evacuation times of precincts comprising buildings with mostly uniform characteristics. The information required for these assessments are similar to single building evacuations. However, these assessments also need to look into interaction of people evacuating from multiple buildings and also people already present on egress paths or destinations.

Initial occupant numbers, location and distribution information will need to be obtained from local councils and building managers. Where real life information is not available the numbers can be based on real occupant counts or code prescribed numbers.

To evaluate the evacuation process it will be necessary to identify the final destination for occupants, i.e. assembly point(s) or mustering area(s). These areas are usually established and designated based on their location, accessibility and "assumed" capacity. For precinct evacuations this can be extremely difficult due to very large numbers of occupants being evacuated. Large sports fields, parks, school yards are among the facilities that can be adopted as a final destination/assembly area. Similar to single building evacuations, in order to ensure efficient evacuation the capacity may be based on pedestrian crowding studies.

Once the "initial occupant numbers and locations" and the "final destination location and capacities" are identified the next stage will be to evaluate movement paths and directions. For multi-building/precinct evacuations the paths to be adopted are most likely going to be walkways, city streets/roads/sidewalks. This will require extensive co-ordination between organisations involved to facilitate road closures, traffic re-directions, etc. The movement paths will need to be evaluated from the perspective of the impact the evacuation will have on regular operations of the surrounding streets, sidewalks and vehicular traffic.

The assembly area(s) for a multi-building/precinct evacuation must be accessible for all buildings involved. The accessibility should be relatively similar and uniform for all buildings involved and no building should be significantly disadvantaged. Generally for multi building/precinct evacuations multiple locations are designated assembly points.

Average width and carrying capacity of egress path(s) must be evaluated similar to single building evacuations. In the context of multi-building/precinct evacuations it is likely that once occupants reach street level the movement columns they form may change directions, move out to the streets, change sidewalks, etc. These actions could disrupt movement or significantly deteriorate movement efficiencies.

The length of the egress path (or alternatively the travel distance) is another factor that could dictate the evacuation time. While it is always desirable to limit the egress path length, due to certain features of an emergency it may not always be possible. These features may include the need to move people away from the emergency which triggered the evacuation, the need to provide egress path capacities that will accommodate large numbers or the need to adopt alternative paths if need be.

Evacuation through general pedestrian traffic areas could lead to counter flows. During evacuations through already occupied city streets this can be a significant problem and will require intervention by authorities. Precinct evacuations will take place while all surrounding, unaffected areas are continuing to function in their usual manner. The vehicular traffic will be

impacted by the precinct evacuation but also will impact significantly on the evacuation and the sidewalks will already be occupied by public.

Majority of these factors will be addressed as part of the planning conducted, however they should also be taken into consideration from the perspective of their impact on the mechanics of evacuation.

Very Large Scale Evacuations

Large scale (i.e. suburb/town/city) evacuations are significantly complex processes. In most instances they will involve some form of transportation with cars / buses / trains / etc. The common pedestrian movement knowledge may not be relevant for large scale evacuations. With large scale evacuations information on initial occupant numbers, location and distribution will need to be obtained from local councils/ municipalities, building managers and even census data. Where real life information is not available the numbers can be based on realistic assumptions/estimations. The concept of final destination for large evacuations is more of a planning and logistics issue. The core problem to be addressed is how and to where to move the evacuees and how to accommodate them at the destinations. The movement paths and directions for large scale evacuations relate to the road network surrounding the area being evacuated and it is an issue of vehicular traffic management instead of pedestrian management. These models are very sophisticated high-end computer models. They may be specific to a particular area or they may be applicable to different areas. The specifics of large scale evacuations are beyond the context of this paper and will not be further detailed other than providing certain examples.

DESKTOP ASSESSMENTS

Prior to conducting any advanced computer modelling assessment it is beneficial to conduct a desktop assessment. In some simple cases the desktop assessment may prove sufficient. The aspects of evacuations that could be evaluated using desktop assessments would include:

a. Review of the plans to identify the most likely egress paths to safety and/or assembly points.
b. Occupant distributions, marked on drawings.
c. Likely travel times for occupants to temporary or permanent safety calculated using hand calculation methods.
d. The capacity of proposed assembly areas from the perspective of accessibility and capacity.

COMPUTER ASSESSMENTS

Computer assessments of evacuations may be also referred to as “crowd or movement simulation modelling”. The key aim of the assessment is to evaluate the pre-evacuation/evacuation/post-evacuation conditions using a special purpose computer modelling software. The scale of the evacuation will generally dictate the type of simulation software adopted:

- Single large building evacuations – Generic modelling software of varying levels of sophistication.

- Multi-building/precinct evacuations – Sophisticated generic modelling software or purpose developed software.
- Large scale (i.e. suburb/town/city) evacuations – Highly sophisticated purpose developed software.

There are two main types of models for simulating crowd movement detailed in the literature [10]:

- Macroscopic models: focus on the model system as a whole and concern collective observable behaviours which emerge from the crowd, e.g., the behaviour of the crowd as a whole.
- Microscopic models: focus on the individual level and concern the behaviour, actions and decisions of individuals within the crowd and their interactions with others

Utilising a combination of both macro and micro levels is reported to be most beneficial. Table 1 provides a classification of models under these two categories.

Table 1 Simulation model categories

Macroscopic Models	**Microscopic Models**
Regression Models	Rule-Based Models
Route Choice Models	Social Forces Models
Fluid Dynamics or Gas Kinetics Models	Cellular Automata Models
	Agent-Based Models

Agent-based models are the most complex and realistic of the simulation models, wherein, occupants are modelled as a collection of intelligent, autonomous, decision-making entities known as agents. Each agent is capable of perceiving and assessing its environment, generating intentions, making independent decisions and performing rational, realistic behaviours according to various sets of underlying simulation rules.

Before starting the evacuation modelling process it is necessary to have some understanding of the phenomenon to be modelled, i.e., the evacuation process. It is also important to understand the particular problem (i.e., the scenario which is going to be analysed) then use the appropriate data. It is also relevant to know how to interpret the results. Therefore, a good understanding of all these steps inherent to the whole evacuation modelling process is required for obtaining accurate results.

For computer assessments the models will require input in relation to:

- Building floor plans / precinct maps / geographical maps
- Initial occupant numbers, location and distribution
- Final destination location and capacity
- Movement paths and directions during the evacuation
- Multiple occupant types (age, gender, ability)
- Occupant characteristics such as travel speeds

- Behavioural factors such as pre-movement times
- The impact of specific aspects of the emergency management plans on the evacuation (i.e. staged evacuations, use of refuge floors, use of lifts for evacuations, etc.)

On the other hand, the output can be in one of or the combination of text, graphics, animation or spreadsheet "csv" or "Excel" format. Typical output information will include evacuation times for each part of a building; overall evacuation times; flow times and rates; occupant movement patterns and indication of queuing and bottlenecking.

The most popular computer modelling software commonly used in fire safety engineering includes Exodus, Steps, Pathfinder, Simulex, FDS+Evac.

CASE STUDIES AND EXAMPLES OF THESE APPLICATIONS

Individual Building Evacuation – Shopping Mall Evacuation

This example is based on the evacuation modelling of a large shopping centre. The modelling was conducted using the Pathfinder modelling software [11] as part of a fire safety engineering ASET (Available Safe Egress Time) / RSET (Required Safe Egress Time) assessment. Based on a code compliant design criteria the total number of occupants modelled was 24,000. Along with a core scenario where all exits were assumed to be available, multiple sensitivity study scenarios were considered with various exit paths and doors being blocked. The modelling demonstrated that the evacuation times for different parts of the shopping centre would vary between 200 and 1100 seconds. (Figure 4)



Figure.4 Shopping centre evacuation model

Sports Arena Precinct Evacuation

The subject Stadium in Hong Kong was opened in 1961 with the current holding capacity of about 7,700 seats. An improvement works by alteration of the architectural layouts were to be carried out which would increase the capacity by 6,682 seats. It is the requirement of the local codes that the sidewalks surrounding the facility must have a holding capacity sufficient to prevent the evacuating occupants from spilling to the streets. The original capacity was

demonstrated to satisfy this requirement and approved by local authorities when the facility was built. It was a requirement of the authorities that the increased occupant numbers should not exceed the sidewalk capacity. To analyse the sidewalk capacities and to demonstrate the code requirements are satisfied evacuation analysis using Simulex software was conducted. Based upon the modelling conducted using Simulex Software [12] it was concluded that the available evacuation holding reservoir provides an adequate level of life safety with respect to emergency egress from Stadium in the event of a fire. (Figure 5).

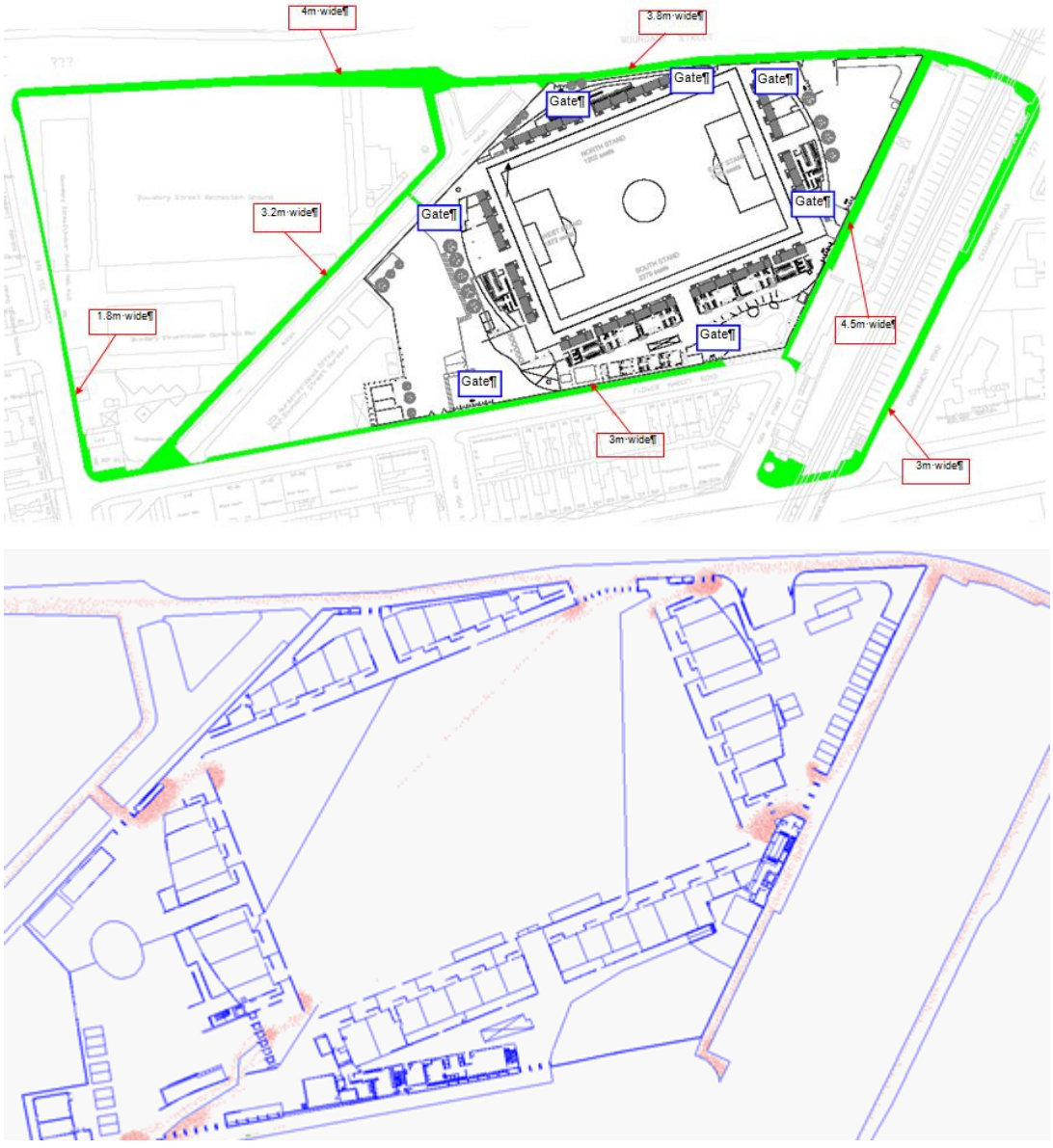


Figure.5 Stadium evacuation model

Office Tower Evacuation Muster Point Analysis

General

A mass evacuation computer modelling assessment was conducted for a large high rise office building. The building has an emergency management plan which requires regular evacuation drills involving two (2) floors at any time. The building management identified the limitations of partial drills and were interested in the efficacy of a full building emergency evacuation and its impact on the highly populated surrounds. Another objective of the

assessment was to evaluate a proposed alternative location to the current assembly area which was identified as being too small and not-appropriate for business continuation plans. Hence, a model was constructed to incorporate the subject building and its surrounds, a bridge and the courtyard of a museum as the assembly area. The distance from the building to the assembly area is approximately 800m. Figure 6 shows the modelled area and provides an illustration of the model.

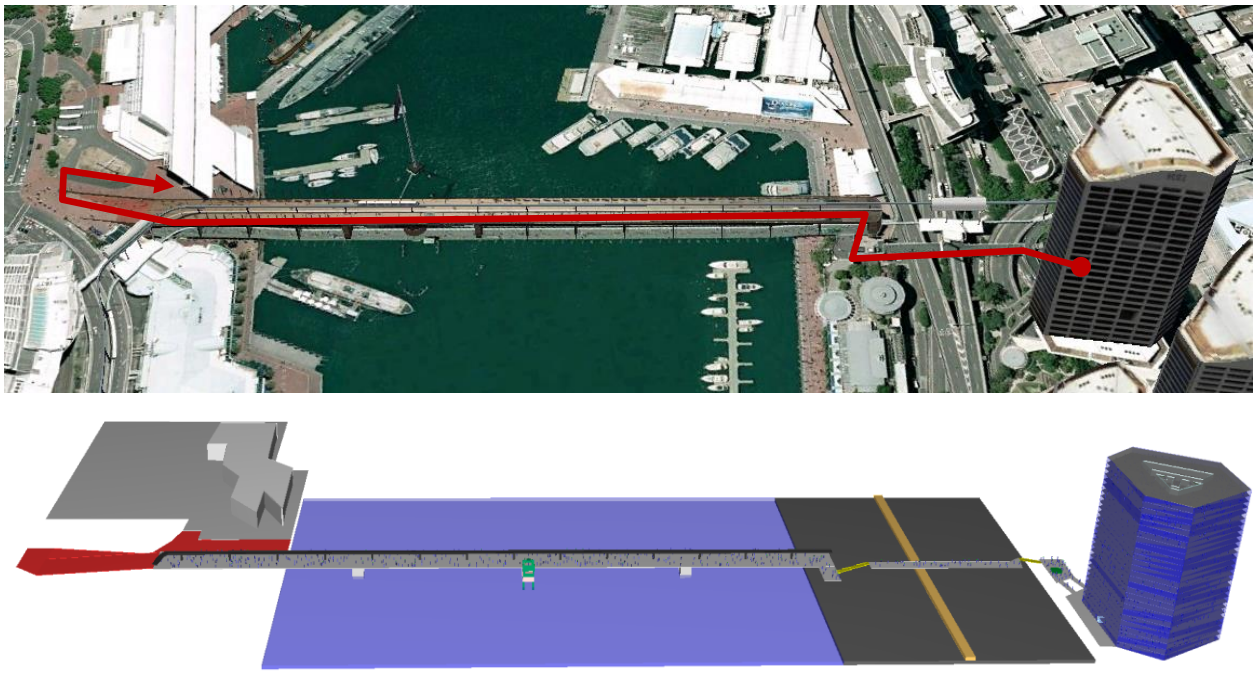


Figure.6 Real life image of the modelled area and the model

The Building Specifications

The subject building which is pre-dominantly occupied by a major bank is 30 storeys in height with51,000 m^2 of net lettable office area. Most levels of the building is utilised as open plan office floors and overall it accommodates approximately 4000 occupants. The current emergency evacuation procedures require occupants to evacuate by means of the two stairs located in the building core. Occupants, once they reach the ground floor, proceed to evacuate through exit doors located on the main street aspect of the building. The procedures then require occupants to proceed to the muster point/assembly area located adjacent to the Bridge. While the area so far has served satisfactorily the purpose of partial evacuations (as demonstrated by annual drills) there is a concern that in the event of a full evacuation it may not be appropriate from the perspectives of capacity and general bridge pedestrian traffic. Therefore and alternative location is proposed across the bridge at the courtyard of a museum. There are a number of advantages of the courtyard as a muster point/assembly area including the following:

a. It is an open area with minimum number of obstructions.
b. Compared to other areas within the vicinity, most of the time it is scarcely populated.
c. The travel path between the Tower 1 building and the assembly area is sufficiently wide and again, clear of significant obstructions.
d. There is a bus turning point adjacent to the assembly area which can be utilised for transport of staff to other locations as part a Business Continuation Program.

The Evaluation

The existing muster point is located at the eastern aspect of the bridge. For evacuation of small number of occupants (i.e. 1-3 floors) this area is identified as being suitable. However, in the event of a full evacuation of the office building occupant numbers approaching 4000 would be occupying 60m or almost 20% of the bridge. This is illustrated in Figure 7.

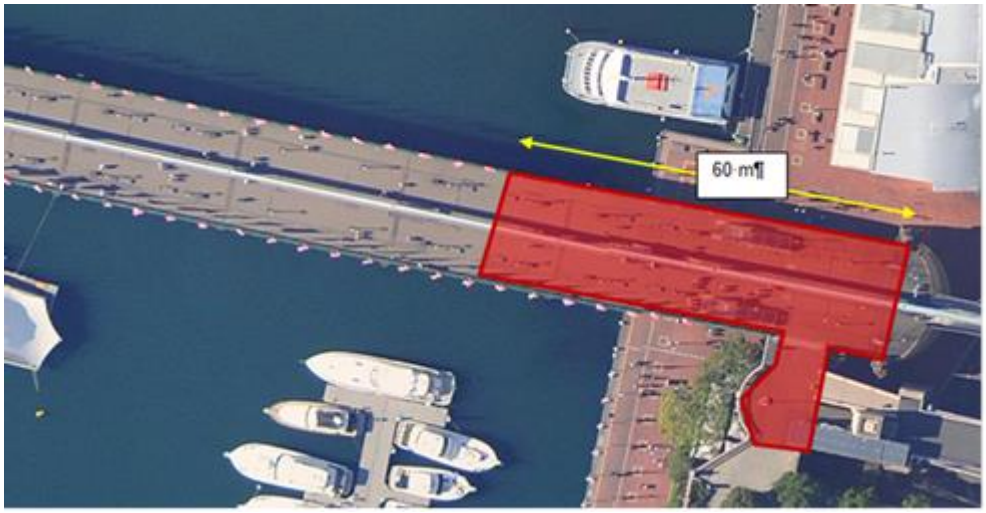


Figure.7 The initial assembly area

In order to evaluate the assembly area capacities it was necessary to establish typical occupant densities during assemblies. Based on the average occupant density of 4 persons/m^2, the area required to accommodate approximately 4000 occupants was calculated to be 1000m^2. The likely extent of a 1000 m^2 area is highlighted in Figure 8.



Figure.8 Muster point/assembly area for 4000 persons.

Evacuation Modelling

In order to analyse and simulate a full evacuation of the office tower building computer modelling has been conducted using the Pathfinder software [12] as shown in Figure 9. The model was constructed to include the building, the courtyard, the path to the existing assemble area, the bridge, the path to the proposed courtyard assembly area and the courtyard assembly area. The model was constructed to estimate the time required for all occupants to travel to the mustering point; back to the DP1 building; and return to the work places within the office building, only using lifts. The estimated times are summarised in Table 2.

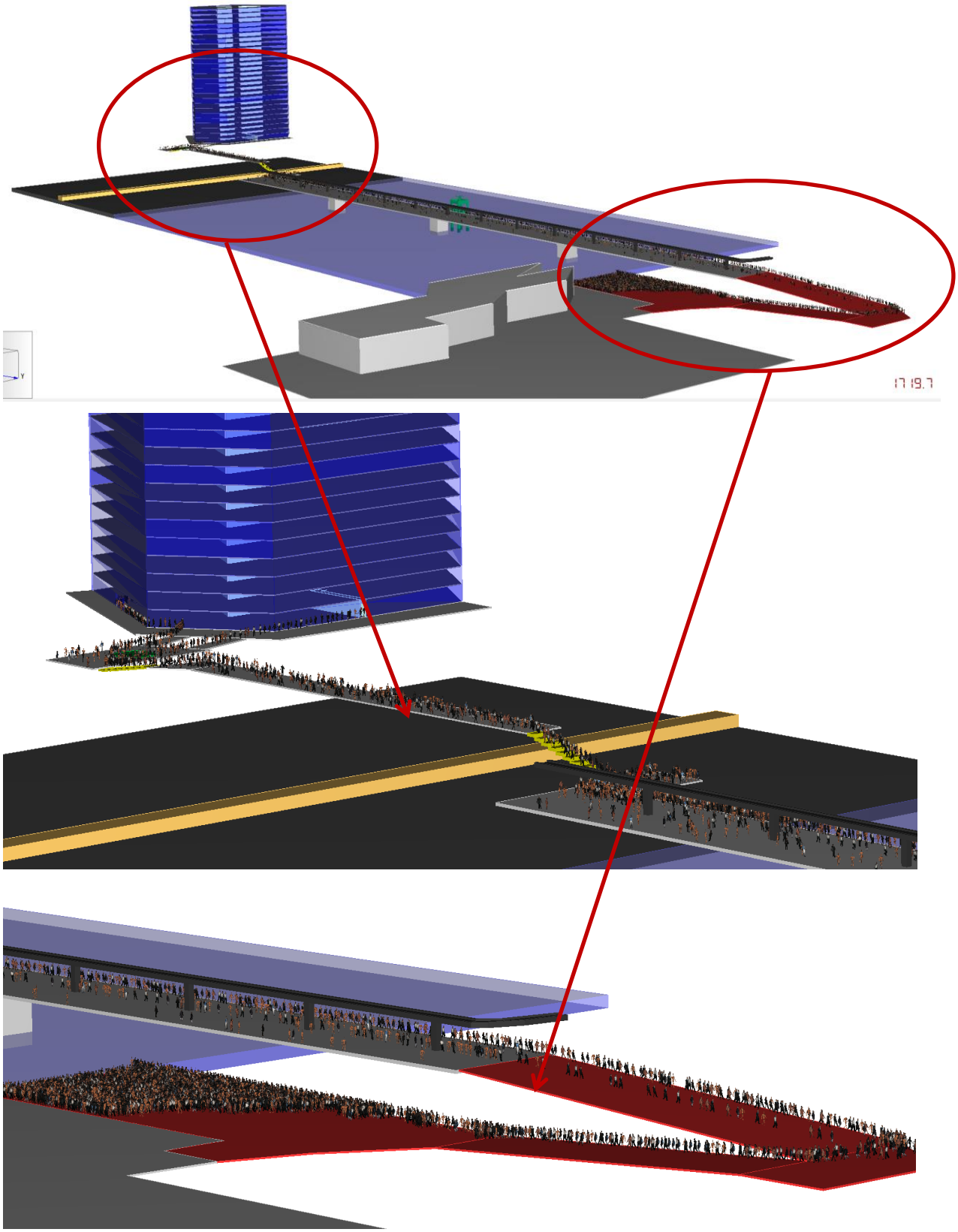


Figure.9 – The precinct evacuation model images

Table.2 – Modelling result summary

	Occupants	**Number of Occupants**	**Event times**
Stage 1: Tower to Assembly Area	Leaving the Tower Building and arriving at the assembly area	3840	**1820** seconds (approximately 30 minutes) for the last occupant to leave the building
			2700 seconds (approximately 44 minutes) for the last occupant to arrive at the assembly area
Stage 2: Assembly Area to Tower(including lift travel back to office levels)	Leaving the assembly area and arriving back at the Tower Building	3840	**570** seconds for the first occupant to arrive back at DP1 (occupants start using the lifts to return to their floors).
			7770 seconds for the last occupant to arrive back at the floor of origin

As a consequence of the qualitative evaluation and the modelling it was concluded that the proposed muster area adjacent to the courtyard would satisfy both the life safety and the business continuation objectives.

CONCLUSION

It is a responsibility of all parties involved in the design, development and management of buildings that are likely to accommodate large populations that an appropriate emergency evacuation plan is not only developed but also tested and analysed. The codes and regulations establish a minimum benchmark in relation emergency evacuation plans. Developing a plan based on codes and regulations will ensure that all legal requirements are satisfied. But, it is a duty of care requirement that the efficacies of these plans are further assessed. Evacuation modelling software may be adopted for this purpose. Use of such software is not limited to individual buildings. They may provide invaluable information in relation to precinct or even larger area evacuations.

ACKNOWLEDGMENTS

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