

PLANNING FOR AN OPEN PIT UNDERGROUND HABITAT

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ABSTRACT

Whilst current and future underground structures in Singapore are conceived as deep basements, shallow and deep caverns, this paper explores the underground structure as an open pit variant of up to 140m depth and 125m in diameter accommodating up to 17000 housing occupants. Daylighting, airflow and evacuation strategies are assessed as a first attempt to ascertain the likelihood of adequate health and safety provisions. How deep can the pit be before ventilation and daylighting are ineffective? How do we evacuate in time, the projected population? Singapore codes are used in conjunction with references to extrapolate benchmarks as a basis for further study and recommendation. Other planning considerations are discussed as integral components of the open pit configuration.

An egress simulation for staggered tower blocks is clocked at 50 minutes for 17000 occupants fleeing upwards, using elevators, staircases and transfer sky bridges. The study also concludes that daylighting of up to 80m depth is possible and airflow between buildings of up to 60m depth is achievable with mechanical ventilation and wind diverting devices integrated with the architecture of the pit. This is subject to building shapes and their arrangement within the space of the pit. Airspeeds between blocks in the pit do not exceed 1.5m/s as the length of buildings blocks is not aligned with the prevailing wind direction to form wind corridors. Instead the N-S building block orientation attempts to maximize daylighting of interiors to reduce energy consumption and reduce solar gains. However inadequate outdoor airspeeds are not amenable to urban health conditions and further studies are necessary to improve both wind and daylight performance in respect of outdoor airspeed within the pit space and hot air circulation out of the pit, the proportion of units obtaining adequate daylight hours and planning for a viable number of housing units given the higher costs of excavation, construction, mechanical ventilation, waste and water management systems required

KEYWORDS

Underground habitat, open pit structure, planning for security and safety, building form, daylighting, urban air flow, egress simulation

INTRODUCTION

Three unbuilt large-scale architectural propositions are cited as a preamble to understanding the motive, context and scale of the underground development.

- i. 1969- Oscar Newman's Underground Manhattan – historic conjecture
- ii. 2009- BNKR Arquitectura's *Earthscraper* in Mexico City – a proposition from an architectural design competition for new ideas in habitat
- iii. 2020- AB Ellis' Siberian Underground City- a developer's proposal to refurbish a disused large scale open pit mine

Whilst Newman's vision was motivated by the provision of defensible space from atomic bombs, Mexico City's solutions were an attempt to address urban sprawl and a lack of large open space for city dwellers.

Newman's Underground Manhattan¹

The underground structure is a massive sphere oddly similar to Newton's Cenotaph. Its volume calculated by John F. Ptak, is 1.2 miles³ or 5 km³ with its top beginning at 1,200 ft beneath Time Square. The excavation is equivalent to the volume of Lake Mead and would engulf the Bingham Coppermine in Utah, which is only 2 miles wide and a quarter mile deep.

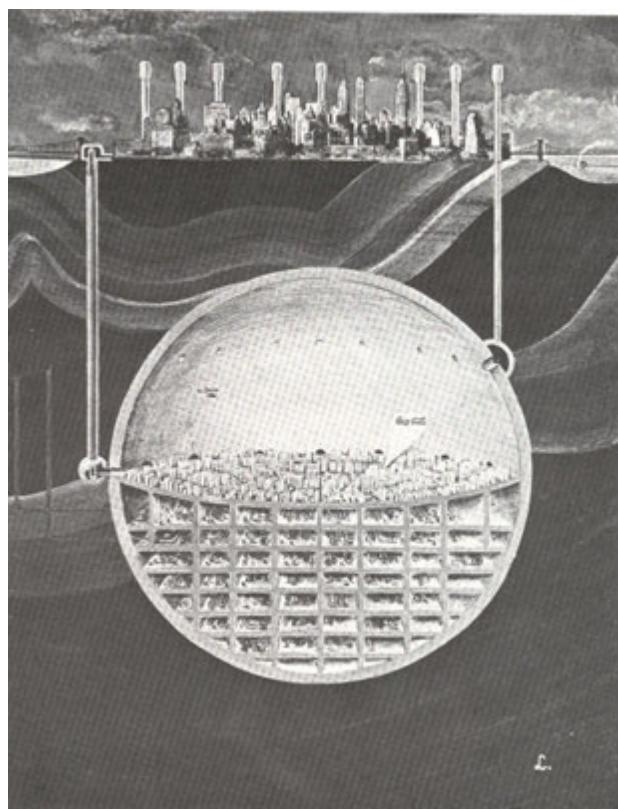


Figure 1: Oscar Newman under Manhattan New York (1969)

To construct this sphere of 1.2 mile in diameter and 3,500 ft deep, the excavation is likened to diverting the Hudson and East rivers whilst extending the digging into Jersey. The hollowed space occupies half the volume of a regular city with a grid of streets and buildings. Air filter towers penetrate the surface to ventilate the sphere. Newman intended for six atomic cities

beneath Manhattan. However the main problem of an underground city is lack of views and fresh air. Given the air quality in New York, air supplied to an underground city has to be filtered and further, the idea of a window view to a neighbor's wall was unappealing.

2020 Underground City in Diamond Mine, Siberia designed by AB Elis

The Siberian project however is a refurbishment of the Mir diamond mine. The second largest excavated open pit in the world, at a quarter of a mile in diameter and 1,700 ft deep, it is planned to accommodate 100,000 inhabitants. A dome will cover the open pit and it will be equipped with solar energy harvesting devices, food farming facilities and life support utilities. The eco city will be constructed of multiple levels with a huge central core. The main floor comprises park and recreation areas with residential areas stepping out around the walls of the mine. Beneath this, spaces for vertical farms and forests kept alive by daylight piped down the central core.



Figure 2: Underground City in Diamond Mine Siberia by AB Elis Architects (2020)

Mexico City Earthscraper by Emilio Barjau, Chief Design Officer of BNKR²

Mexico City has a population of 9 million within 573 miles² and 19 million people in the greater metropolitan area. It faces the challenge of liveable spaces with large populations in dense urban settings. In comparison,

- Sao Paolo has a population of 10.65 million people
- New York has 8 million people within 302 miles² (783.8 km²) and 18.9 million people distributed over 6,720 miles² (17,400 km²)

The *Earthscraper* is in the 188,976 sq. ft. Zocalo, the city's major public plaza and physical centre of its history and culture. The plaza hosts year-round civic events such as concerts, exhibitions, public demonstrations and parades. The *Earthscraper* preserves its surrounding landmarks such as the Templo Mayor (a main Aztec temple), the Metropolitan Cathedral and the National Palace.

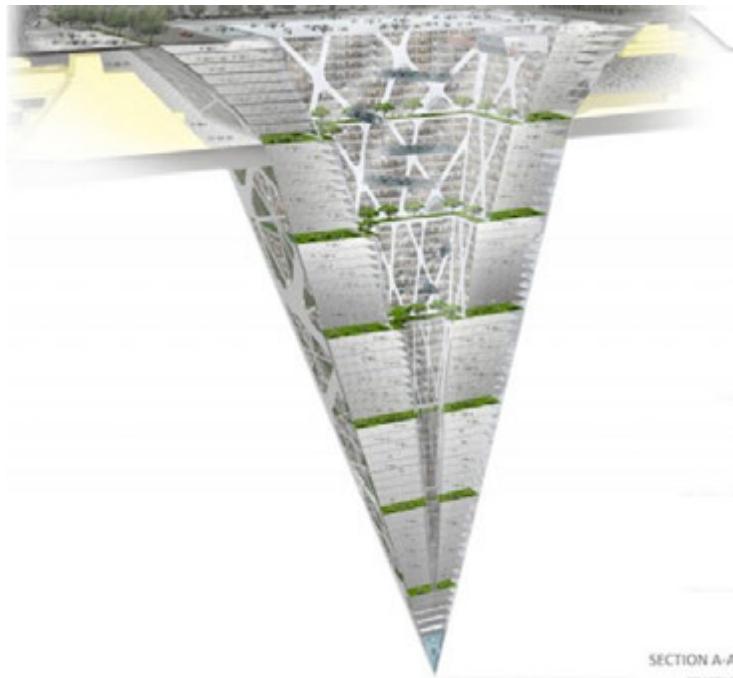


Figure 3: BNKR Arquitectura's Earthscraper beneath Mexico City (2009)

The *Earthscraper* starts with a glass roof replacing the opaque stone surface of the Zocalo. This preserves the open space and civic usage of the square while allowing natural light into the underground pyramid. All cold walls to the tapering structure are clear or translucent. The inverted pyramid is distributed as such - the first ten storeys is a museum displaying the excavated layers of Mexico City since pre-Columbian times. The next ten storeys are retail space followed by another ten storeys of apartments. The structure's deepest tapering 35 floors are for office space.

Whilst 15,000 parking spaces would normally be required for such a development, the concept omits parking in favour of promoting connections to Mexico City's public transport system, the largest in South America. The concept is to contain different activities and 100,000 people within the centre instead of spreading traffic and pollution 360 degrees around. The *Earthscraper* would be insulated by earth while the gardens would create micro-climates inside the tower. The interior has a system of gardens every ten storeys to generate fresh air. It is proposed that no HVAC systems will pull in air from outside in order to save energy.

When constructing in the water table, builders will need to find a way to excavate into the water-soaked soil, which supports contemporary Mexico City. After the Spaniards drained Lake Texcoco in the 17th Century, parts of Mexico City have sunk as much as 30 ft into the soft clay bed. The city continues to pump wastewater and run off out of the valley to prevent flooding. Groundwater and wastewater are among the greater challenges of the design, and ways to consider using water around the side, filtering it into the building before returning it to the earth.

In a hot climate, building underground removes many ventilation opportunities and the glass roof traps heat inside acting as a greenhouse.

The assumption of Land Saving

Newman's model of an artificial sky with ventilators for a spherical entity saves on ground level land usage in providing for a secure environment for additional population. However the immense challenges of excavation and construction were not known to be technically realizable at that time. Such a 'sealed' environment would imply fully mechanized means of climate control and in the provision of utilities.

Whilst the Siberian proposal is a refurbishment of an industrial site, it shares with the Mexican proposition land saving measures an added advantage of being spatially integrated with above ground site contexts.

Notwithstanding these challenges, the idea of an underground habitat conceived as a large open pit has its challenges in construction and in operation. It is essential that such habitats are defensible and provisions be made for the safe evacuation of its inhabitants.

The paper discusses planning considerations for an open pit version of an underground settlement for under 20,000 people.

PROVISIONS FOR INHABITANTS

1. Security and Emergency

The investment of an underground structure must be protected from any threat to the integrity of its entire system that would compromise the safety of its inhabitants and of surrounding above ground environments. More vulnerable to sabotage, flooding, subsidence, earthquakes, heat build-up, haze, fire and vermin infestation, the planning of underground structures cannot be naively based on non-threat scenarios.

What then are worst-case scenarios?

Atmospheric contamination, acid rain and airborne viruses make living conditions unsafe. Food production is compromised by air, water and soil quality; and is also hampered by ecological imbalance (e.g. vermin and pest population increase and resilience to pesticides)

It is necessary to plan for potable grade water supply and food production in adequate quantities and for unlimited periods of time, to meet the consumption of inhabitants in situations of military siege. Food and water wars necessitate the securitization of food farms, water resources, grain storage pilfering, raiding and sabotage. Aquifer supplied water should have secure withdrawal points, protected from poisoning or contamination.

Sunlight may be inadequate for health and food production, and inaccessible due to air contamination when coal combustion and forest fires persist intermittently and incessantly.

For these reasons, underground structures should be sited near reliable and defensible sources of water to sustain food production. Sustainable means of producing substitutes to sunlight, ventilation, fresh water in food production processes and daily living also need to be further studied.

2. Spaces for large population accommodation need to be planned for riot control, surveillance, and protection from vermin and the prevention of air and waterborne cross-infection

Siting for defensible locations is a primary consideration. Lessons from military precedents are useful guides. General Chiang Kai Shek's Shilin Residence was planned as a fortified villa atop a hill with deep continuous balconies acting as ramparts for sentry patrols. Camouflaged amidst the aesthetic landscape, an escape tunnel from an underground command post led to a concealed location for vehicular egress. As a whole, the villa was designed to conceal its inhabitants and to mislead assassins.

Underground escape routes leading to places of refuge must be fire protected and undetected by enemy, be defensible against drone technology, and tunnel boring. Thus, the use of sally ports (originally in World War 2 bunkers) needs to be considered with the threat from new invasive weaponry. Pathways are planned for clarity to escaping inhabitants but which can deliberately mislead invaders. Mazes, which entrap are nested in escape routes and codified for inhabitants. Codification may involve paving patterns or lighting fixtures, which are discernible, even in panic situations.

Evacuation procedures may involve the supervised movement of groups of inhabitants from one compartment or holding centre to another, before reaching the surface. If the surface is no longer a viable option of refuge then alternative refuge compartments need to be accessed via multiple escape routes. Emergency access routes have to be secure and protected from smoke, flooding and ventilation failure. Defence, emergency and security personnel need to be located at the upper recesses of each ring to provide a line of defence and along the depth of the underground structure to facilitate an evacuation plan undetectable by invading forces.

What are the numbers of subdivided populations to guide planning for security, psychological, environmental and health provisions?

How do we design an open pit structure to overcome the vulnerability of air raids and chemical weapons?

How is the underground structure planned for post nuclear survival?

In an airstrike, the camouflage of open pit structures will need to safeguard their location visibility from GIS and heat detection systems. The Iraqi forces employed the scrambling of satellite images from ground apparatus.

For these reasons, the outer ring of the pits need to be designed as defensive fortifications from land and airstrikes whilst accommodating devices to render military detection systems ineffective. Once this line of defense is breached (when settlement structures within the open pit are being destroyed) evacuation networks and emergency shelters become operational. Air raids necessitate the provision of shelters within the walls of the open pit.

3. Utilities

In order for shelters to be effective population-protection measures, they require air circulation and should not lack drainage, nor be prone to dampness and floods.³

Sewage and waste disposal engineering is also a major consideration for the

underground settlements. Waste recycling and reclamation technologies enabling decentralized and compact facilities occupying small footprints are useful. This raises the question of land saving. Open pit entities can occupy open space in the urban fabric or in a landscape field or nature reserve. In these cases, new or additional buildings including infrastructure that do not occupy space above ground will retain the character and scale of open sites or low rise urban fabrics.

Waste management, water and biofuel reclamation technologies may be integrated within pit structures. When conceived in this manner, the underground structures save land by integrating waste facilities with those for the provision of utilities. Wastewater reclamation with compact membrane reactors and rainwater management may be planned to reduce the costs of connection to city treatment facilities.

The capacity of district scale cooling plants may be reduced and integrated with pit structures by designing open pit settlements with some measure of natural ventilation and effective daylighting.

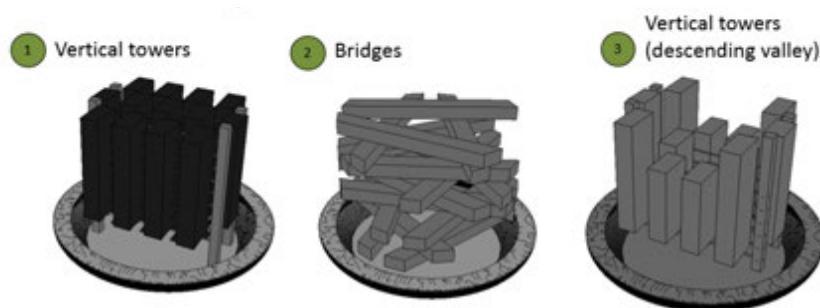
DAYLIGHTING

The open pit configuration interprets open spaces for inhabitants to allow access to daylight for half the total daylight hours in a day. In this respect, where intermediate sky gardens between blocks would obstruct daylighting to the lower recesses of the pit, placing communal open spaces only at the lowermost level of the pit and on the rooftop surfaces of building blocks would be feasible studies in solar gains.

1. Analysis

Daylight factor for dwelling and food farming purposes were made. An entry for the Duxton Plain competition was adapted (scheme 1) to study the effects of spacing between blocks, block shapes, block heights and block positions on daylight provisions and the extent of natural ventilation for an open pit of 125 m diameter and 140 m deep.

Housing units were modelled as vertical tower and bridge blocks; and daylighting as well as ventilation of airspace between blocks were compared.



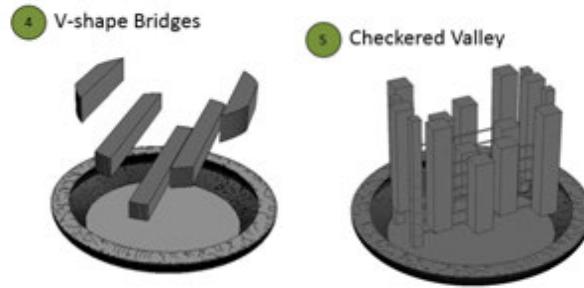


Figure 4: Five schemes were analysed

Scheme 1 Vertical towers

The simplicity of vertical towers in Scheme 1 allows for more efficient daylight penetration on the east & west facades as compared to Scheme 2. The design is however susceptible to varying daylight performances due to sun-path and orientation. Given the orientation of blocks with shorter faces facing North-South and sky gardens on every floor, the facades only receive half the opportunity to benefit from daylight. East façade for instance, receives daylight only in the day, later half of the day will be shaded. When compared on a general scale (façade average), Scheme 1 is minimally better performing than Scheme 2 - Scheme 1 with maximum depth at L33, and Scheme 2 with maximum depth at L35.

Scheme 2 Bridges

Due to the stochastic orientation of bridges, bulk of direct sunlight has been denied for bridges located below Deck 9. Bridges above act as shades for the bridges below, therefore attributing to the low daylight levels.

Schemes 1 and 2:

Given the objective of achieving full daylight penetration for all units, both schemes are considered under-performing, as only 11-18% of the total number of units receives adequate daylight. The majority of units will have to completely rely on artificial lighting sources.

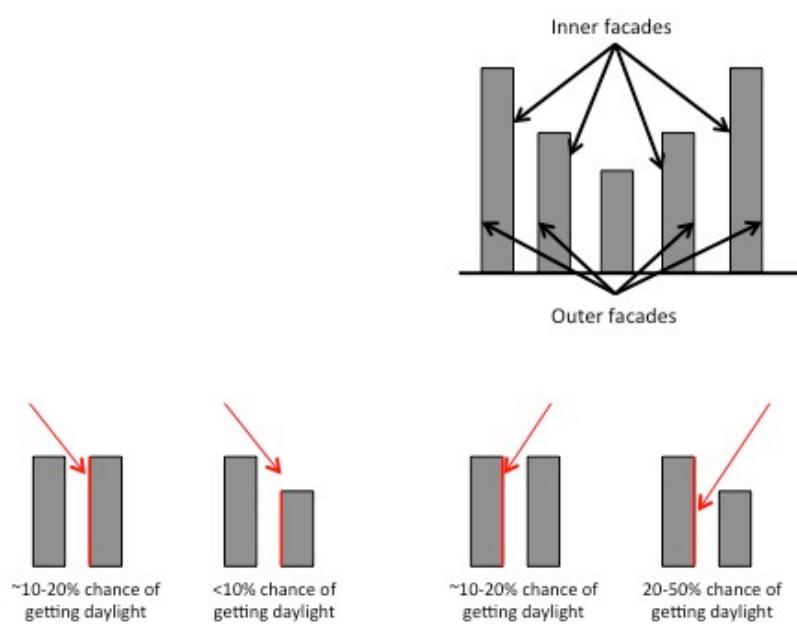


Figure 5: Percentage of daylight received for Scheme 3

Scheme 3 Vertical towers (descending valley)

Scheme 3 staggered building heights in an attempt to correspond to sun path. It hypothesized that by creating a “valley” by varying building heights, at least 50% of the facades in each of the tower is guaranteed direct exposure to sunlight and therefore potentially better daylight performances. All sky gardens between blocks were removed.

Various trade-offs have been observed. Whilst the valley allows inner facing facades to be directly exposed to sunlight, the taller towers contrastingly almost always shade the outer facing facades. Also, creating the “valley” to achieve better daylight performance reduces the number of housing units to 1800 units compared to 2080 units when maximizing full height in Scheme 1.

Generally, Scheme 3 is better performing in achieving adequate daylight, with deeper penetration depths of L23, 10 storeys more than Scheme 1.

Scheme 4 V-shape bridges

Scheme 4 explored a more systematic placement of bridges to form a ‘V-shape’, much like the valley created in scheme 3. The same hypothesis stands that by staggering bridge positions to form a “valley” arrangement, at least 50% of the facades in each of the tower is guaranteed direct exposure to sunlight and therefore potentially better daylight performances. Again, creating the V-shape has proven to achieve better daylight performance (with depths of L14) but the number of housing units is reduced to 512.

Scheme 4 has about six hours of daylight per day at sky gardens to all blocks. This is adequate for the growth of the full range of vegetables as an estimate of its urban farming potential.

Scheme 5 Checkered Valley Towers

In an attempt to increase the spacing between tower blocks by removing half the built up volume of each tower block in Scheme 3 to create a checkerboard pattern, the number of units reduced from 1800 in Scheme 3 to 824. There was an increase in the depth of daylight penetration (15 m in Scheme 3 to 42 m in Scheme 5) and an increase in the number of units receiving daylight (200 in scheme 3 to 314 in Scheme 5). This was in spite of the shadows cast by the sky bridges between blocks.

2. Conclusion for Daylight Analysis

Out of these five schemes, the roofs for Schemes 2 and 4 were included in the daylight analysis of walls (facades). The method of analysis contributed to these two schemes having the highest depth of daylight penetration. Thus for open pit arrangements, using the roof (instead of walls) is a better option in daylighting units within the pit. The daylight effectiveness of the roof plane suggests horizontal blocks as a better performing option compared to vertical blocks.

Scheme 4 shows the best potential in reaching the desired daylight performance criteria with maximum daylight penetration depths as deep as 78m from the top (L14). Surprisingly, Scheme 2 allows for most number of units that is able to receive daylight. The horizontal blocks are concentrated along the rim, allowing daylight to permeate the surfaces of blocks

deeper into the pit, from the central void space.

Based daylight analysis for 21 June, residential units in open pit structures can receive daylight up to a depth of 80m (equivalent to 26 storeys). However, having to construct underground structures within the 80m will require the understanding of trade-offs between having adequate daylight and having sufficient housing units.

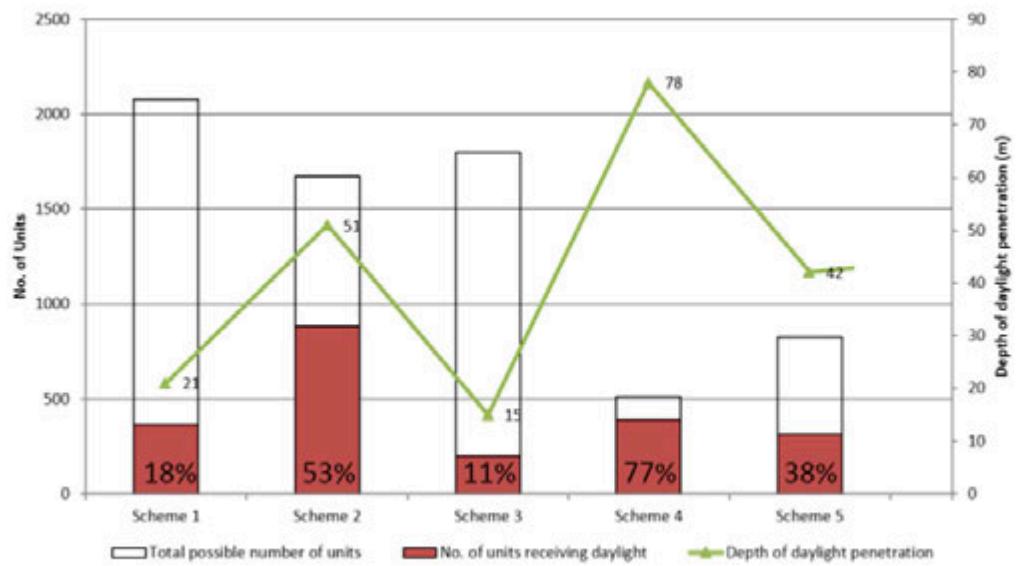


Figure 6: Daylight performance of 5 schemes

VENTILATION

The first concern is stagnant air and heat build-up at the bottom of the pit.

Airflow, ventilation and temperatures in high-density urban conditions are compromised by the heat island effect. Whilst daylight penetration to the bottom of the pit might reduce solar gains and the likelihood of superheated hardscape radiating heat, ventilation may be difficult if airflow and wind speed is insufficient.

1. Stagnant air

Can wind speeds at the deepest part of the pit between buildings enable sufficient circulation to avoid stagnant air? When the wind speed is zero in a natural condition outside the pit, how do we create airflow? How can airstreams be diverted into the airspace of the pit between buildings?

2. Heat build-up

How can hot air leave the pit? (heat is discharged from buildings into the pit air and radiant heat is anticipated from sun struck surfaces of the pit)

From the Singapore MET data, wind speed of up to 2.0 m/s at 15 meters above grade was used as a starting point to study the diversion of airstreams into the pit and the extent of air circulation at the bottom of the pit. Whilst wind speeds in the interior of dwelling units are recommended at 1.0 m/s, the Building Construction Authority's (BCA) norm is taken as 0.5m/s, a wind speed of 1.5 m/s is assumed as a target for wind speed between buildings. However, Ng's Comfort Outdoor Temperature Chart recommends speeds of 2.5m/s, 4.0m/s and 5.0m/s respectively for sitting, standing and walking.⁴

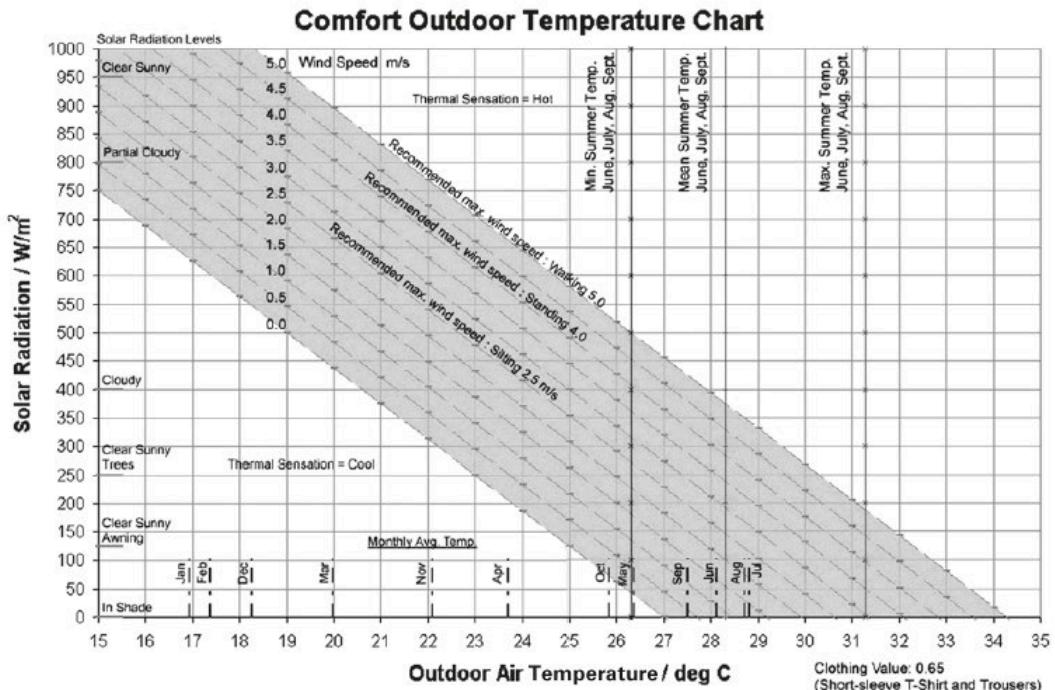


Figure 7: A comfort outdoor temperature chart based on survey data in tropical cities
Source: Edward Ng, *Designing High-density Cities*

Most of the airstream skimmed over the pit opening because the pit diameter to depth aspect ratio is 0.89. Dr M Czech, *et. al.* recommends an aspect ratio of 2.0 for pit diameter to depth.⁵ The two-block type arrangements were studied with variants to each.

3. Summary of findings

Rooftop scoops at a height near the pit top (*Ronchamp* Belfry) were ineffective in diverting the airstream downwards. The angle of the scoop was too steep and turbulence was experienced instead of effective downward diversion.

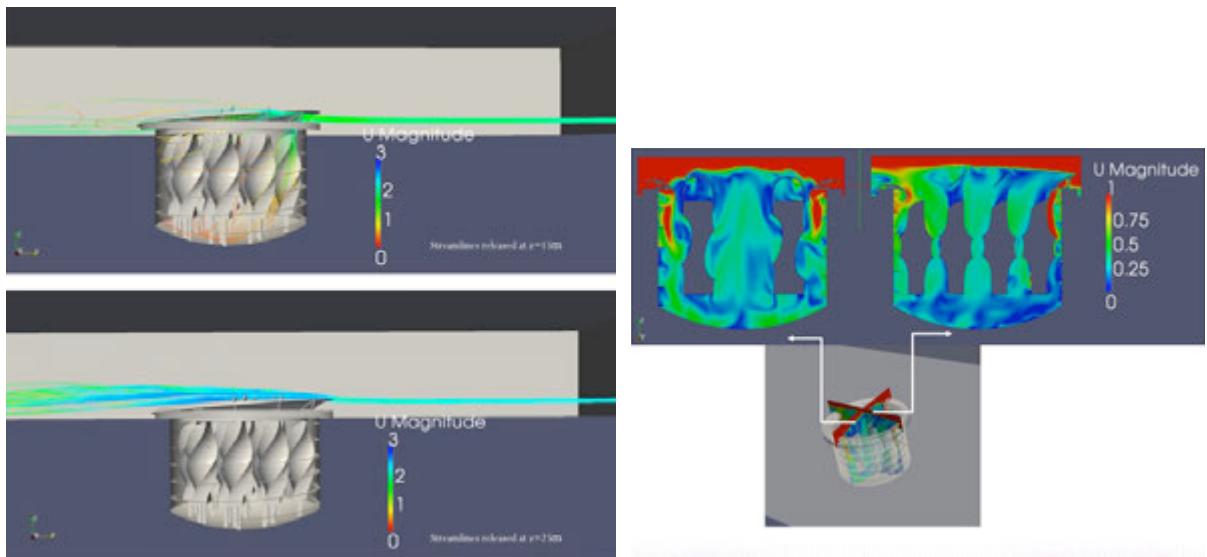


Figure 8: (Twisted towers) Single blade is not adequate.
Ronchamp scoops do not accelerate airstream.

Three modifications to form were introduced to assess the effectiveness of wind diverting devices at strategic locations.

- i. rooftop air scoops to individual towers
- ii. a ring aerofoil above the lip of the pit
- iii. housing block form

A double blade foil was more effective than a single blade foil at 15m height above the pit lip. Only the windward portions of the aerofoil were effective (up to 60% of the pit circumference on plan needs to be kitted with an aerofoil). Aerofoils may be deployed as pneumatic structures for seasonal direction change. The pit lip when shaped as an inclined berm acts as a funnel with the aerofoils, was more effective than an upright parapet.

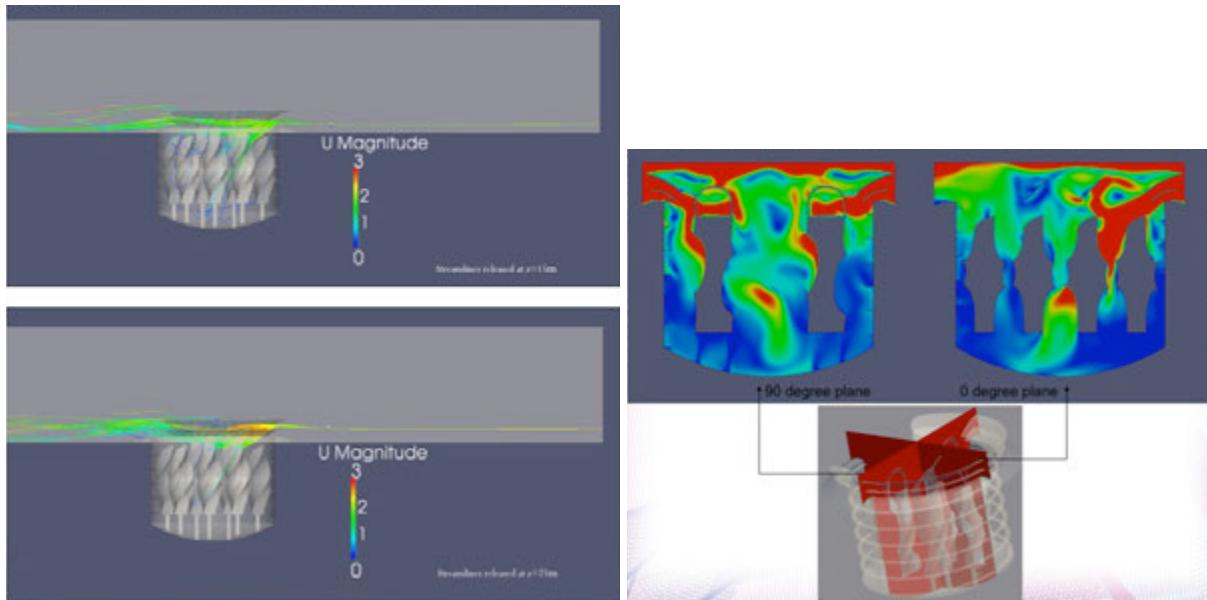


Figure 9: (Twisted towers) Double blade has a down draft effect which is good but rooftop scoops are not effective for leeward blocks.

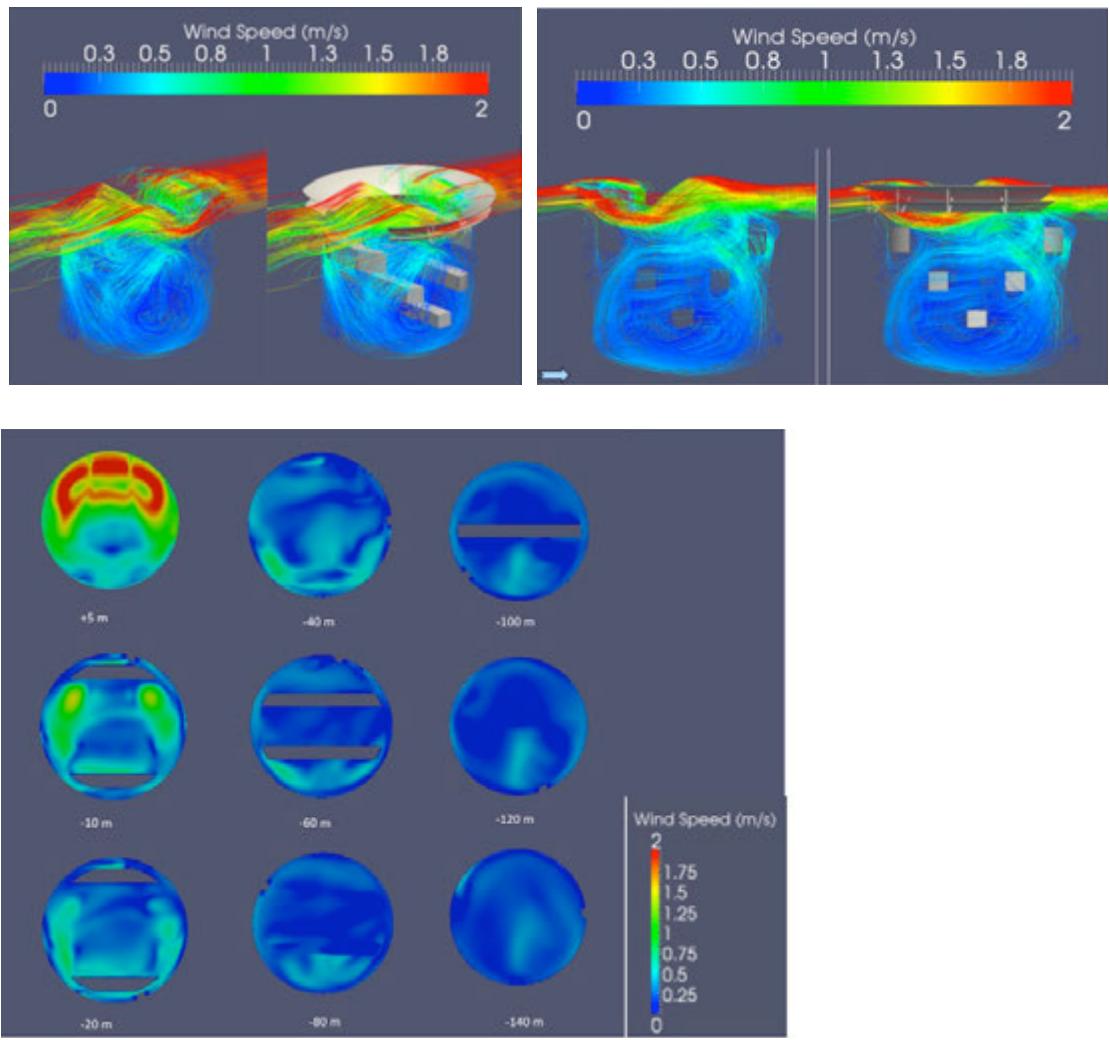
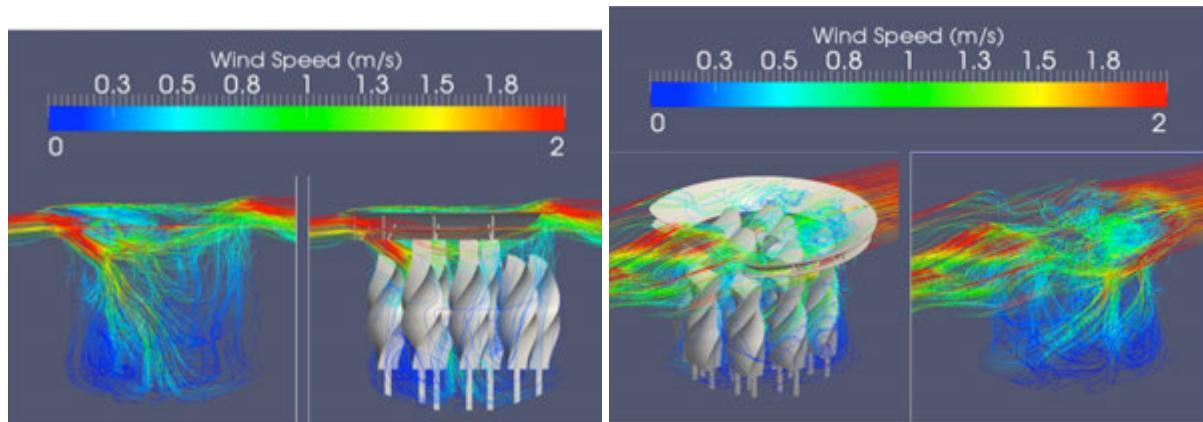


Figure 10: (Parallel bridges) Double blade aerofoil has limited benefit - only up to -10m



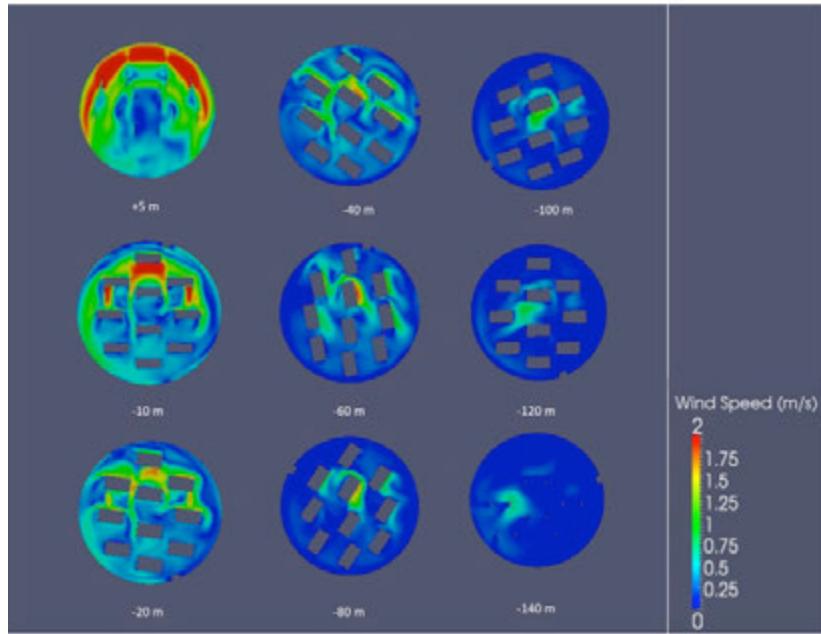


Figure 11: Twisted towers with enhanced double blade*
Airstream extractors from levels 20-30m can improve the airflow and speed by augmenting the effects of the double blade foil with natural ventilation.

Stepped tower blocks and twisted spiral tower blocks channeled the air downwards to the pit base but not sufficient to achieve 1.5 m/s. Stepped valley bridge blocks with wider spacing performed best.

Thus, airflow within the pit is affected by:

- i. the arrangement of built forms within the space of the pit
- ii. the spacing between built forms
- iii. the shapes of the built forms
- iv. the double bladed aerofoil in effect pushes an upper airstream layer onto a lower layer and diverts wind into the pit
- v. the funnel arrangement of both blades in the sectional plane accelerates the wind speed marginally (*the enhanced double blade has its top blade elongated at its trailing edge)
- vi. the aspect ratio of pit opening to pit depth

EGRESS SIMULATION

Given the arrangement of discrete vertical towers in a large open pit, the evacuation of the housing component is simulated with inhabitants fleeing from the bottom of the towers to the top.

1. Method

A commercial software package (Pathfinder) is used to simulate pedestrian movement and to investigate the occupant evacuation time. It uses the SFPE method to solve the governing equations for occupant evacuation behavior.

2. Occupancy load

Scheme 3 – Vertical towers, is used for study with 17,056 occupants.

In the Singapore Fire Code - for residential projects, the fire occupancy load is computed at 15m^2 per person, for children's playground, it is $5\text{m}^2/\text{person}$ and for a roof garden, it is $1.5\text{m}^2/\text{person}$.

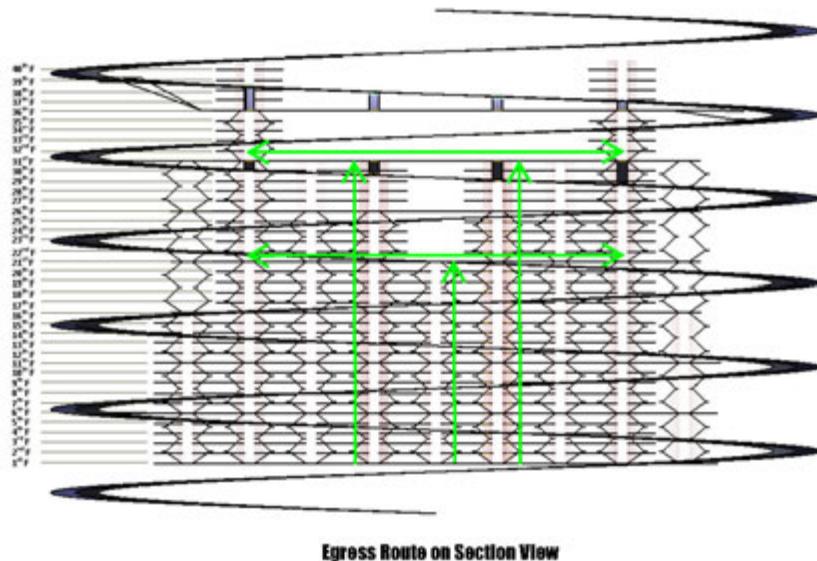
3. Configuration constraints

The centre portion of seven shorter towers is an attempt to reduce daylight obstruction to housing units nearer the base of the pit. Thus only four towers have elevators that reach the top of the pit and connect to the rampways exiting at the top of the pit. This means that the inhabitants escaping from the remaining nine tower blocks have to access these four towers by transferring across sky bridges at levels 21st and 31st in order to escape upwards. There are four fire escape lifts and two fire escape staircases per tower block.

4. Evacuation Sequence

The evacuation time limit is not to exceed one hour.

The evacuation plan is to use 52 fire lifts (13 blocks x 4) and 26 fire escape staircases as illustrated in Figure 12. All the blocks are evacuated simultaneously via the individual lifts and staircases. The lifts evacuate the occupants from the bottom to the top levels.



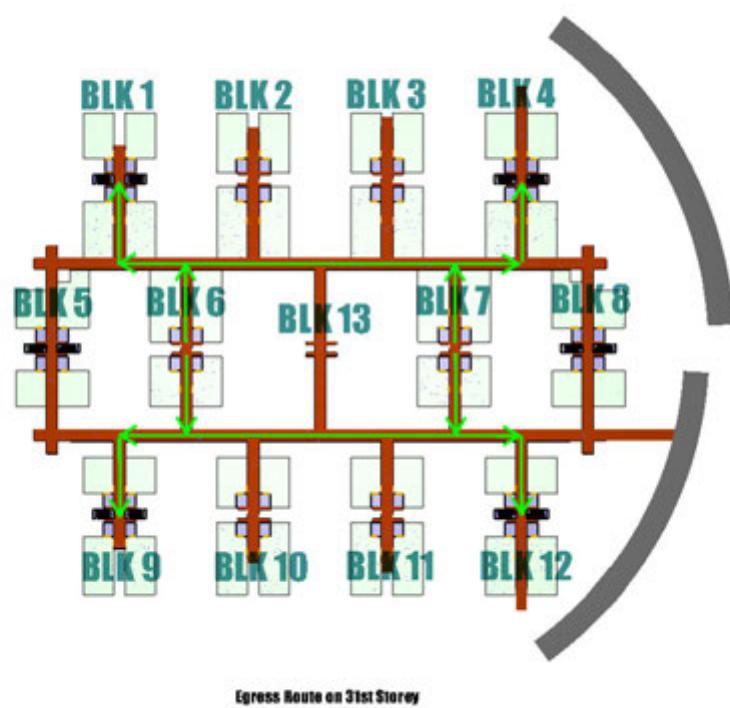
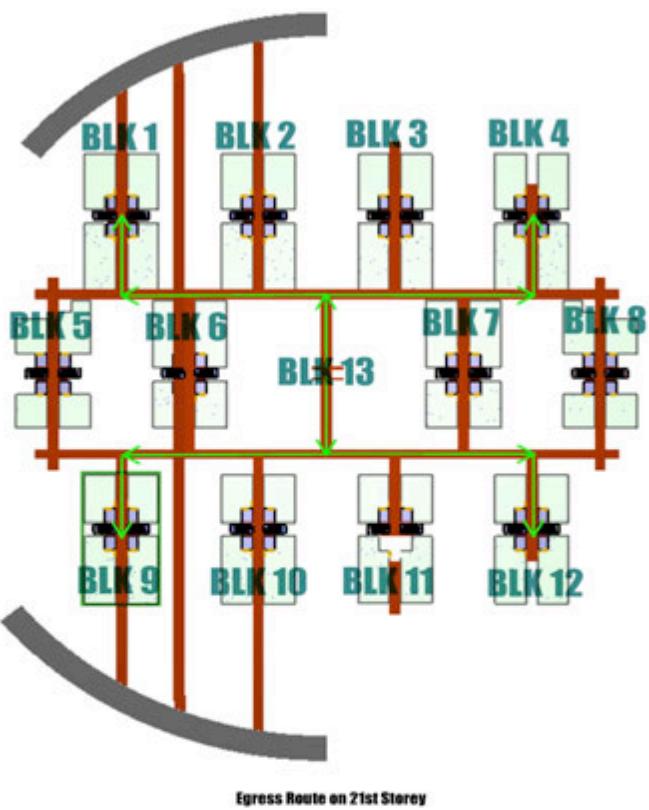


Figure 12: Egress route in a fire evacuation

270 people are anticipated to gather at each block lobby. Whilst 144 people take the lift (36 people x 4 lift cars), the remaining 126 people will use the escape staircases. The lifts evacuate the occupants one storey at a time i.e. occupants from each storey are brought to the refuge place without stopping at other storeys. (It is a conservative assumption that the lifts are not on full load during the entire evacuation). When all occupants from the first storey have been evacuated, the lift will evacuate occupants from the second storey, and so on.

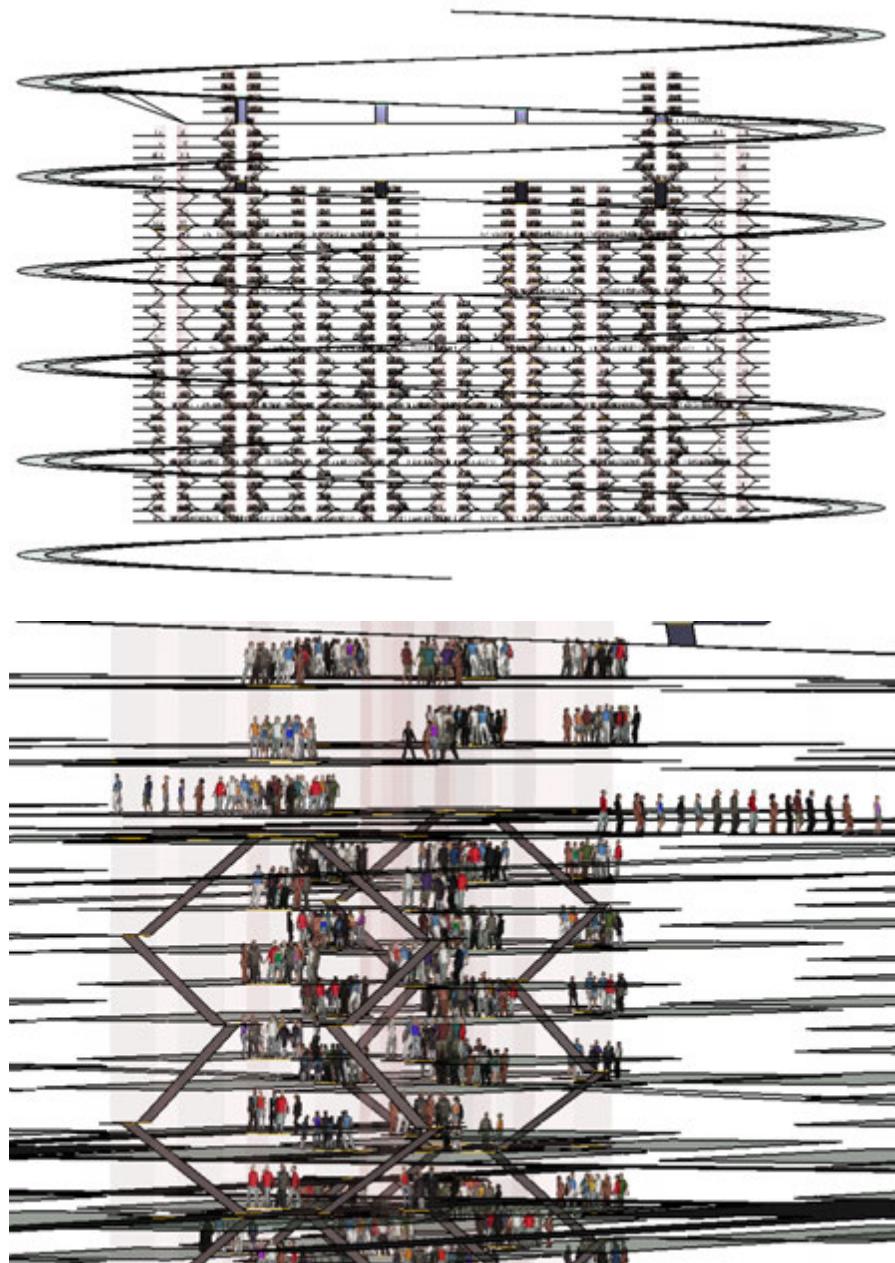


Figure 13: Occupant evacuation simulation via the provisions of lifts and staircases

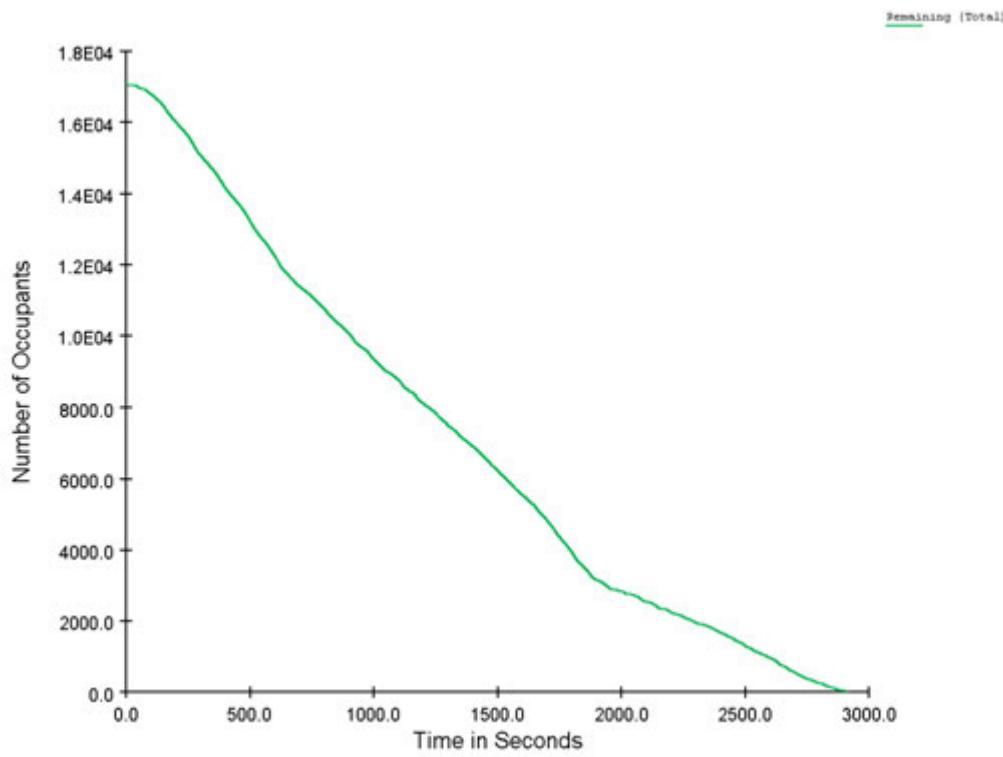


Figure 14: Rate of evacuation

5. Conclusions on Egress Simulation

The maximum capacity of the fire escape lift used in the model is 36 people/car. One evacuation cycle carries approximately 1,872 people (via 52 fire lifts). So, to evacuate 17,000 occupants, the total evacuation time is less than 50mins. The travel distance and egress capacity complies with Singapore's fire code requirements.

6. Recommendations

The simulation concludes that the combined egress provisions of fire escape staircases, transfer sky bridges and lifts are adequate to evacuate the 17,056 occupants within 50mins.

However, sky bridges as a principal means of transferring occupants from one tower to another have to be fire protected for up to 4 hours. To accommodate the waiting times of escape elevators, the escape widths of sky bridges and lift lobby landings may be enlarged at critical locations i.e. at levels 21st and 31st. Currently, the width of corridors, sky bridges and staircases are estimated at 2m.

STRUCTURE AND CONSTRUCTION

The structural and constructional implications on design strategy and form are as follows:

- i. design excavation props and scaffolds as permanent structure
- ii. structure is conceived as evacuation route
- iii. structure must be failsafe against flooding, heat build-up and earthquake

If the excavation costs are substantial, then elements used in the excavation process such as rampways and lateral struts may be designed as permanent structure for usage and habitation.

Structural beams spanning the diameter of the open pit act as struts to the outer retention walls. Such beam struts resist forces from the surrounding earth, subsoil water, earthquake and erosion displacements acting on the retention wall structure of the pit. Such structural elements increase in scale when the basements displace larger volumes of earth. Consequently, there is a need to research stiffening strategies without incurring excessive dead loads.

If deadweight is a significant design problem to overcome, then novel foundation systems need to be explored. What is the possibility of using groundwater where available or stored rainwater to provide the buoyancy for floating inner basements in multiple sleeve structures? Structural integrity and serviceability may be provided with more than one structural layer, compartmentalized, to seal off localized leakage or structural punctures.

SURFACE WATER MANAGEMENT

Flood control and rainwater discharge/ discharge are key areas of research. What forms of flood and rainwater control can generate structural and mechanical strategies for deep underground structures? What are viable depths including operational costs?

One possibility is to design the inner wall of the open pit structure as a deep raft floating in a rainwater cistern contained by an outer wall. The advantages are three-fold:

- i. reduction in the costs of foundation
- ii. stormwater management and drinking water supply is integrated with overflow tanks accommodated within the cavities of the retaining walls
- iii. water is used to maintain a consistent temperature within the pit interior by minimizing contact with the earth and the effects of fluctuating or changing earth temperature

OTHER EXPLORATIONS

1. Structural studies as Density Morphologies

When land is scarce or too expensive, would it be worthwhile to consider subterranean alternatives? The research question would be to explore forms of settlements that can accommodate underground population densities equivalent to above ground counterparts.

If the capacity of an underground structure were to hold more people than those aboveground then, where would these forms of increased capacity lie within the physical structure?

Studies on types of structural earth and water retention systems capable of accommodating interstitial and protected spaces within diaphragm and buttress elements (design of space accommodating structures) can be large scale civil engineering works.

Morphological studies on hybridizing retention structures with habitual forms of dwelling and as accommodation for security forces can be explored.

2. Sustainability

In an age of carbon responsibility what is the impact of an underground settlement with respect to emissions? The following research areas are necessary.

- i. Resilience in energy source
- ii. Heat exchange and heat expulsion
- iii. Reducing waste removal by closing waste-material-energy loops
- iv. Water supply and flood management

For a viable proposition, the energy costs of sustaining safe and healthy habitation in underground systems should not outweigh:

- i. the advantages of freeing up land space at ground level for premium yield rates
- ii. the guaranteed protection and security from disasters and be defensible against all forms of military attack including the ability to withstand a siege for indefinite periods of time
- iii. the overall reduction in carbon emissions from mechanical systems which are required in lieu of natural light and air movement
- iv. capacity of accommodating more people per square metre of surface than in above ground systems

3. Landscape

Landscape may be considered in three ways for the open pit proposition.

The approach to the pit lip from intruders may be taken from tank traps and infantry traps designed in the Maginot Line.

Landscape measures may be provided cool the air stream before entering the pit. This relates to the siting of open pit structures away from heated city hardscapes where air temperatures are high and airspeeds are reduced.

Landscape may be interpreted as oxygen gardens and edible landscapes within protected chambers accessible to light. The inside faces of the pit can be landscaped in a way so as to prevent high solar gains. Scheme 4 has sky gardens with sufficient daylight hours for vegetable cultivation.

4. Emergency provisions

There were plans to rebuild Kobe after the 1995 earthquake into a grid plan of clear access ways leading to emergencies shelters and treatment facilities at grid intersections. The rest of the city was to be planned around the establishment of this emergency grid system. Solutions for disaster management in the context of underground structures will not be confined to individual open pits but more likely as a network connecting discrete open pits.

The accommodation of emergency rescue vehicles, large-scale refuge centers and hospitals determine the physical plan of the emergency network components with protected UPS provisions.

5. Corrosion

Underground structures need to be designed against forms of corrosion caused by subsoil

conditions, which act on the external structure. Similarly, corrosion sources acting on the internal surface of the structure need to be considered when planning and when specifying building material.

How long do we design underground structures to withstand corrosion? What are life cycles of key and ancillary components? How do we plan for replacement and refurbishment?

In conclusion beyond the construction challenges, the proposal of any large-scale underground structure involves complex considerations, which must necessarily anticipate worst-case scenarios in operation given its extensive reliance on life support and emergency systems. Most importantly its location in relation to existing site contexts necessitates environmental impact studies and a future for re-use upon decommissioning. Unlike above ground structures, large scale underground structures are not simply demolished or filled up after being left in disrepair.

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References

¹ Alison Sky and Michelle Stone, *Unbuilt America* (McGraw Hill 1976) pp192.

² Emily Gertz, *Ecomagination*.

³ Risby Peter N 'Air Raid Shelters: The Anderson Shelter.

⁴ Edward Ng, *Designing for Urban Ventilation*. Designing High-density Cities for Social and Environmental Sustainability, Earthscape (2009) pp126.

⁵ Dr M Czech, Prof N Toy, Mr T Mavrides, Prof S Okamoto, Prof P J Disimile, Mr L Gaudet, Cavity Flows. Faculty of Engineering, The University of Western Ontario.