INGENUITY AND INTELLIGENT RISK ASSESSMENT FOR RESILIENT GEOTECHNICS

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ABSTRACT

Geotechnical engineering is a risky business and there is much that can, and does, go wrong. It is often said that the single most common cause of failure in construction (including delays and additional costs) is in the ground. This would indicate that the logical path to design more resilient infrastructure would be the adoption of over-conservative designs. However, the in-ground structures that collapse often have a number of fundamental and basic design flaws. In reality, most in-ground structures move considerably less than predicted at design stage, suggesting that they were, in fact, over-designed. Over-design can also be considered a form of failure as it can add cost and delays in construction. It is generally accepted that a resilient piece of infrastructure is not necessarily one that does not fail upon a catastrophic event, i.e. one that is overdesigned to withstand such event. Otherwise the concepts of sustainability and resiliency would be conflicting. A resilient design is one that does not cause significant disruption to the community and can function effectively as quickly as possible after the catastrophic event.

So, how can geotechnical engineers achieve resilient infrastructure designs? The best approach seems to be associated with intelligent risk assessment that is based on an in-depth understanding of how such a design will perform before, during and after a catastrophic event. This approach requires good knowledge of the fundamental principles of geotechnical engineering such as solid mechanics, geology, failure mechanisms and so on. This paper will discuss some of the requirements for intelligent risk assessment and presents a practical example of an approach that could be adopted for the design of resilient infrastructures. Its primary focus is on the anticipated performance during a potential failure and the intelligent risk assessment forming the basis of the entire design.

1 INTRODUCTION

The International Tunnelling Association (ITA-AITES), in its 2013 Global Perspective Programme – "Deciding on Better and Resilient Cities", stated that the world today is facing many challenges. One of these is that the world‟s cities will need to accommodate 6 billion people by 2050 and by then it is estimated that 70% of the world‟s population will live in urban areas. This fact alone poses a major challenge for urban planners. Imagine the world‟s population now, all living in cities - this is what the figure of 70% in 2050 represents. Rapid urbanisation is one of the world‟s major challenges. Natural disasters and the changing climate are the second major challenge facing the world. The effects of climate change, notably as freak weather occurrences, are now a recurring global phenomenon. This has enormous impact on mega cities. Earthquakes, tsunamis, major storms and flooding on a massive scale, are threatening the fabric of society and cause massive disruption. Cities need to learn to cope with this challenge and ask themselves how resilient they are to such events.

These challenges have been identified by the United Nations as major issues that require policies and action at a global level. UN Habitat is running the World Urban Campaign which has the theme „Better City, Better Life‟. The basis of this programme is not only to raise awareness but it is also a true call to action. It requires engaging the public at large, the civil society, the business sector, the research community and governments in a global movement. The campaign includes a vision of what sustainable urban development requires. However, sustainable urban development calls for resilient cities and asks cities to consider and prepare for natural disasters. It also asks cities to plan for these events. How does this affect geotechnical engineering?

Geotechnical engineering is a risky business and there is much that can, and does, go wrong. It is often said that the single most common cause of failure in construction (including delays and additional costs) is in the ground. This would indicate that the logical path to design more resilient infrastructure would be the adoption of over-conservative designs . However, the in-ground structures that collapse often have a number of fundamental and basic design flaws. In reality, most in-ground structures move considerably less than predicted at design stage, suggesting that they were, in fact, over-designed. Over-design can also be considered a form of failure as it can add cost and delays in construction. As a result, it is also generally accepted that a resilient piece of infrastructure is not necessarily one that does not fail upon a catastrophic event, i.e. one that is overdesigned to withstand such event. Otherwise the concepts of sustainability and resiliency would be conflicting. So what is resilient infrastructure design?

A resilient design is one that does not cause significant disruption to the community and can function effectively as quickly as possible after the catastrophic event. So, the third question is, how can geotechnical engineers achieve resilient infrastructure design?

Joan Clos, the United Nations Under-Secretary-General, Executive Director of UN-Habitat in 2013, made a statement that contains the essence of the answer:

> *"We need to demonstrate that change is possible through the genius, creativity and audacity of people and decision-makers to make the wisest choices for our urban future."*

As cities face the task of climate change adaptation and focus on resiliency, creative thinking is required. Contemporary solutions no longer provide the answers. In geotechnical engineering, the answer seems to be associated with two words: ingenuity (in agreement with Joan Clos above) and intelligent risk taking.

Intelligent risk assessment requires in-depth understanding of how a geotechnical design will perform before, during and after a catastrophic event. This approach requires good knowledge of the fundamental principles of geotechnical engineering such as solid mechanics, geology, failure mechanisms and so on. This paper presents an example of such design approach that was adopted for a temporary case but has, in its essence, the concept of intelligent risk assessment and therefore could be adopted for the design of resilient infrastructure. Its primary focus was on its anticipated performance during a potential failure and the risk assessment forming the basis of the entire design.

2 THE IMPORTANCE OF FUNDAMENTALS

As mentioned above, intelligent risk assessment requires in-depth understanding of the basics and fundamental concepts of geotechnical engineering. On one hand, the collapse of in-ground structures exposes severe flaws in understanding of fundamental concepts of ground behaviour and geotechnical engineering. On the other, most in-ground structures move considerably less during construction and operation than predicted at design stage, suggesting that they were in fact over-designed - also a form of failure. According to Atkinson (2008), the relatively high incidence of failures in geotechnical engineering indicate that geotechnical engineers are not as competent as they should be, or as we would like them to be.

When asked to define the typical characteristics of sands and clays, most geotechnical engineers would say that sands are granular and frictional and clays are cohesive. They would also answer that, upon rapid loading, sands would behave in a drained manner and clays undrained. These concepts, although generally accepted for most practical purposes, seem to be easily challenged by everyday experiences, including those we have as children. For example, Figure 1a, would seem to indicate a cohesive sand while the dry area around the footprint in Figure 1b demonstrates the undrained behaviour of a dense sand. The former is a demonstration of pore water suction and the latter a demonstration of the concepts of constant volume shearing generating negative excess pore-pressures due to a dilative behaviour. As a result, the terms granular and cohesive to describe soils are misleading (Atkinson, 2008). Both sands and clays are granular, i.e. they both consist of individual particles, and both may have "cohesive" strength. Soils should be described as coarse-grained or fine-grained as grain size (strictly pore size) is the fundamental aspect that controls suction and drainage and therefore their behaviour.

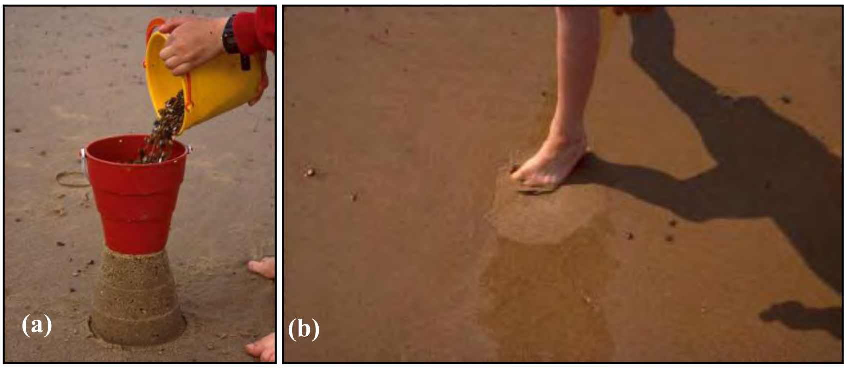

Figure 1: (a) Unconfined compression of sand. (b) Undrained shearing of dense sand (after Atkinson, 2008).

Another concept that is fundamental to geotechnical engineering is the principle of effective stress and geotechnical engineers must have a clear knowledge of it. They must understand the difference between drained loading, undrained loading and consolidation. They must know when to carry out analyses in terms of total or effective stress.

In other words, the principle of effective stress underpins all geotechnical engineering but its application is often misunderstood. A well-known example is the 2004 collapse of the cut and cover structure for the Circle Line Stage 1 adjacent to the Nicoll Highway in Singapore. One of the main contributing factors was the incorrect application of a numerical model involving the assessment of undrained strength through effective strength parameters. The original design analysis of soil-structure interaction was carried out using finite element methods with a linear-elastic perfectly plastic Mohr-Coulomb (MC) model representing the soil behaviour. The use of this soil model together with drained effective stress strength parameters (*c*‟, ϕ‟), in an undrained setting, greatly overestimated the undrained shear strength of the local marine clay leading to a serious underestimation of computed wall deflections, bending moments and mobilization of forces in the jet grout pile-raft at the base of the excavation (Whittle and Davies, 2006). The overestimation of the undrained strength is associated with the uncoupled shear and volumetric behaviour of elastic-plastic models underestimating the generation of excess pore-pressures and resulting in a vertical effective stress path in isotropic elastic models as depicted in Figure 2 below.

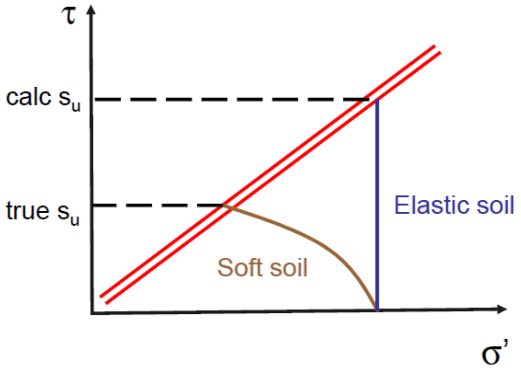

Figure 2: Effective stress path for an isotropic elastic soil compared to true soft soil behaviour.

Soils and rocks behave differently under different applications and there are a variety of combinations of parameter values and factors applicable to different design limit states. Geotechnical engineers are often unclear about the relationships between, for example, peak, critical state and residual strengths and factors of safety and load factors (Atkinson, 2008).

It is important to note that there is no discussion in this section about the correct use of standards or codes of practice. The discussion above is around basic competencies. Competence requires the engineer to get the basics right; it does not require the engineer to follow a code or standard. Without these basic competencies, the target of resilient geotechnical design is unattainable.

3 INTELLIGENT RISK ASSESSMENT

As discussed above, a resilient piece of infrastructure does not need to be over-designed to fully withstand a catastrophic event but to have the extent and magnitude of any impact caused by a failure controlled such that it does not cause significant disruption to the community and can function effectively as quickly as possible after the event. To achieve such controlled failure it is essential to have good knowledge of the fundamental principles of geotechnical engineering, such as ground behaviour, failure mechanisms, as discussed in the previous section. Once these basic competencies are achieved, the geotechnical engineer has the tools to appropriately assess the problem at hand and adopt a more risk based design which focuses on delivering a resilient piece of infrastructure.

2.1 RISK BASED DESIGN

Risk is part of every human endeavour. From the moment we get up in the morning, drive or take public transport to school or to work, until we get back into our beds (and perhaps even afterwards), we are exposed to risks of varying degrees. What makes the study of risk fascinating is that while some of this risk bearing may not be completely voluntary, we seek out some risks on our own (speeding on the highways or gambling, for example) and enjoy them. While some of these risks may seem trivial, others make a significant difference in the way we live our lives. It can be argued that every major advance in human civilization, from the caveman‟s invention of tools to gene therapy, has been made possible because someone was willing to take a risk and challenge the status quo. This seems reasonably in line with the statement of Joan Clos cited above regarding the "…*genius, creativity and audacity of people*…". Although it seems reasonable to accept that to combine sustainability and resiliency in infrastructure projects, risk taking is essential this should be based on a thorough understanding of the likelihoods and consequences involved in a potential failure, i.e. intelligent risk taking.

2.2 PRACTICAL EXAMPLE

In order to illustrate the concept above, a practical example of a risk based design is presented here. This example is based on a remedial design carried out by Coffey for a 35 m high existing slope/embankment supporting a highway that was assessed to have unacceptable risk levels (low factor of safety against instability of around 1 to 1.1), though not all design details are provided herein.

The design focused on a temporary solution using a sheet pile wall that would address the risks associated with a potential failure of the embankment without necessarily improving its overall stability (i.e. global factor of safety in the vicinity of one was still accepted as long as the risks were mitigated) allowing the construction of remedial measures that would improve the global stability of the embankment to acceptable levels in the long term. The results of the geotechnical analysis of the existing embankment and sheet pile wall were then used as input to a risk assessment approach (RTA, 2011) adopted to evaluate the effectiveness of the design as a temporary solution.

Although the example presented here is for a temporary solution, a similar approach is possible when assessing catastrophic events where it is practically impossible to design against a failure without overdesigning and conflicting with the concept of sustainable design, but where the design solution should manage the risks associated with a potential failure during such events.

2.2.1 Design philosophy

Generally, the purpose of any support measure is to provide a minimum factor of safety, typically between 1.2 and 1.3 for a temporary condition (often acceptable for a catastrophic event, e.g. earthquakes), such that there is a low probability of failure. In other words, in the conventional design of support measures it is necessary to target a sufficiently low risk of failure, particularly if life is at risk. Under this philosophy, there are circumstances (e.g. catastrophic events) where the support measure may not provide such factors of safety due to the nature of the disaster or possibly the scale of the problem.

A new design philosophy was proposed which focuses on managing the risks of a potential failure mechanism by mitigating the likely consequences. The solution would no longer aim to improve the overall factor of safety of the slope but to force the path of least resistance against slope instability downslope of a sheet pile wall to be installed close to the crest of the slope. As a result, the upper section of the slope, which contains the highway, would be retained by the sheet pile wall for sufficient time to allow for emergency response, such as a road closure, if required. This approach achieved a Roads and Maritime Services (RMS) Assessed Risk Level (ARL) of 4 for "Loss of Life" for a short duration while the permanent solution of an earthfill stability berm was constructed. The design philosophy aims to provide a temporary sheet pile wall such that:

- In the event of a failure downslope of the temporary sheet pile wall, movement is expected to be at a rate such that there will be enough warning for emergency response, if necessary.
- A detailed program of real-time monitoring is implemented to reduce the risk to construction workers and road users of embankment failure.

It is important to note that although the above philosophy is not a design approach typically adopted even for temporary solutions, it is based on conventional engineering principles which mainly focus on addressing the risks of progressive collapse. For instance, fire and earthquake engineering often do not aim to avoid a building collapse but target for enough time during such events to allow for evacuation.

Following such principles, the US National Institute of Standards and Technology (NSIT, 2007) recommends that to reduce the potential for progressive collapse in buildings, the design should consider the assessment of alternate load paths whereby a review of the strength and ductility of key structural elements is required to investigate whether the structure would be able to "bridge" over the initial damage, i.e. to redistribute stresses, but with enough ductility to avoid brittle failure and its propagation. This approach typically requires specific attention to the structure‟s redundancy, ductility and capacity.

As a result, the proposed sheet pile wall promotes redundancy within the embankment reducing the probability of failure propagating towards the carriageway even though the overall factor of safety remains the same as before implementing any temporary measures. For example if a substantial slope failure in front of the sheet piles (mechanism A) is assessed to have a factor of safety (FS) = 1.1 with "Likelihood" L3 in accordance with the RMS Guide, i.e. an annual probability $P(A) = 10^{-2}$, and the likelihood of the sheet pile wall failure before the highway can be closed with sufficient warning (mechanism B) is assessed as $P(B) = 10^{-3}$, the probability of the failure propagating to the carriageway will be lower than $P(B) = 10^{-3}$ as it is a function of both probabilities. As a result, the probability of a failure propagating to the highway and causing loss of life would be significantly reduced even though the minimum FS = 1.1, i.e. lower than generally targeted in design.

2.2.2 Preliminary design of sheet pile wall

As discussed above, the main design concept of the sheet pile wall is to force the path of least resistance against slope instability downslope of the sheet pile wall, i.e. a slope failure can still occur but the slip surface with the lowest factor of safety is located in front of the temporary sheet pile wall. In addition, adverse impacts on the highway resulting from a slope failure are managed. As a result of this potential failure, a large volume of soil would move downslope, thereby forming a batter which is flatter than the pre-failure slope angle. The upper portion of the slope would then have to be temporarily supported by the sheet pile wall to avoid propagation of the failure towards the carriageway. This mechanism is depicted in Figure 3 below.

The simplified method for estimating failure induced embankment deformation as proposed by Khalili *et al.* (1996) has been adopted. A slow failure mode was assumed based on the rate of movements observed on site. The dynamics of a slow failure mode is represented schematically in Figure 4. In this figure, an unstable soil mass is shown at its initial and final condition, i.e. before and after failure, where the centre of gravity moves from point *A* to *B*. The weight of the soil mass is represented by *W* with *O* and *R* being the centre and radius of the slip surface, respectively.

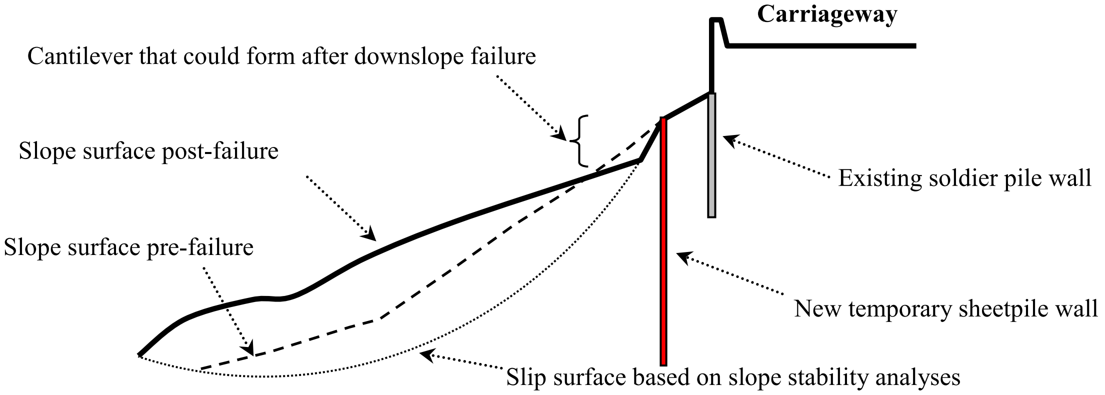

Figure 3: Sheetpile wall concept.

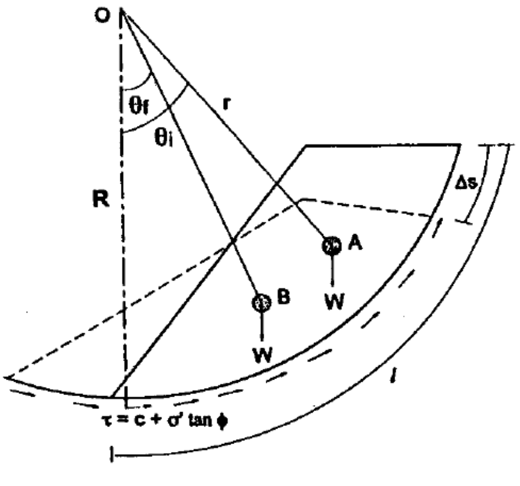

Figure 4: Failure induced slope deformation model (Khalili *et al.*, 1996)

For a slow mode, inertia forces resulting from the movement of the sliding mass can be assumed as negligible, thus, the unbalanced mass will gradually move down the slope until it attains a new stable condition with a factor of safety of unity. Under such large movements the final factor of safety is related to the residual shear strength of the soil. Therefore, the final angular position of the centre of gravity of the unbalanced soil mass, θ_f, can be estimated if the initial angular position, θ_i, and the residual factor of safety, $FS_{residual}$, are known. The final slope geometry may then be estimated from the assessed value of θ_f. It is important to note that $FS_{residual}$ is the factor of safety using the residual shear strength but for the original slope geometry, i.e. prior to failure.

Adopting residual strength parameters considered appropriate for the prevailing ground conditions, a minimum factor of safety $FS_{residual} = 0.73$ was assessed such that the volume of unstable soil mass was considered to be significant, i.e. with scale of failure S1 and volume, $V > 20{,}000$ m^3, with potential significant adverse impact on the highway (Figure 5).

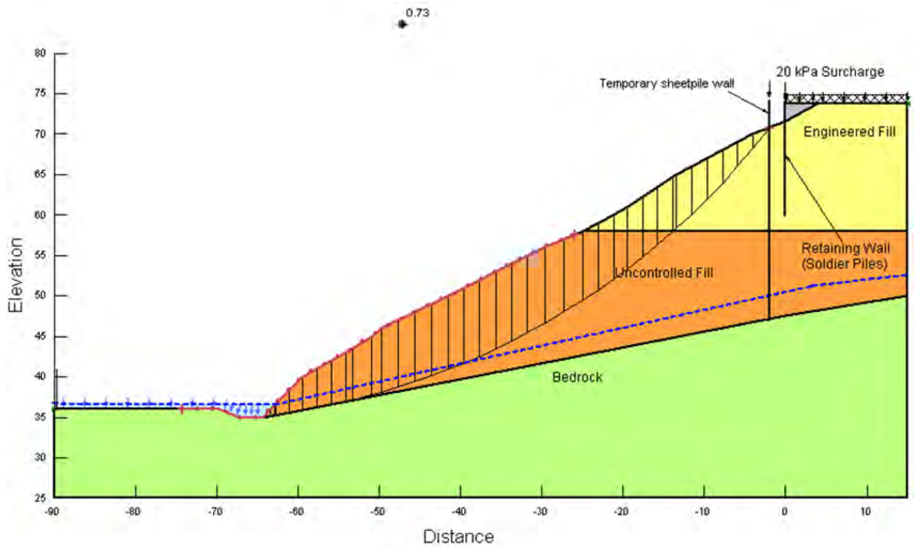

Figure 5: Residual factor of safety for design of sheetpile wall.

Adopting the value of $FS_{residual} = 0.73$ and the slip circle geometry from Figure 5, the failure induced displacements can be assessed using the simplified method proposed by Khalili *et al*. (1996). This assessment indicates that the failed soil mass would reach limiting equilibrium when the slope achieves an average angle of approximately 20º to the horizontal. Considering further failure immediately in front of the sheet pile wall, a cantilever height of up to 6.5 m was considered possible to develop as a result of the movement of the failed soil mass. A 6.5 m high cantilever sheet pile wall within sloping ground was then modelled using the commercial computer program WALLAP. The simplified model is shown in Figure 6 below.

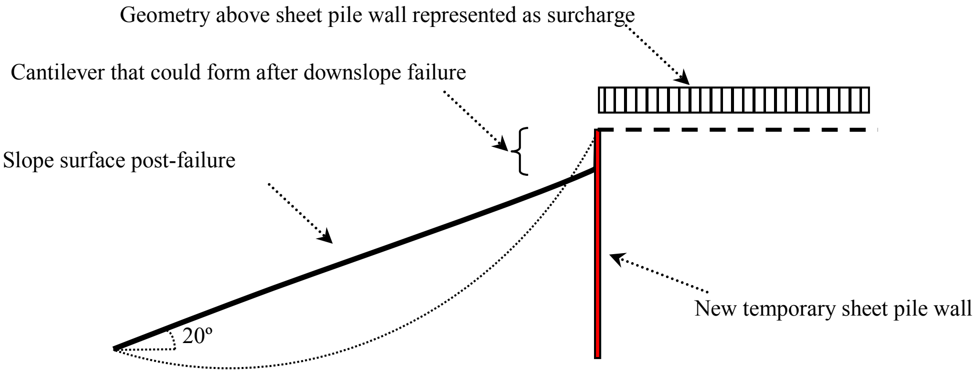

Figure 6: Simplified temporary sheet pile wall model adopted in WALLAP

The soil properties used in WALLAP were assumed to be the peak values as the residual values would only be applicable to the shear zone (i.e. in the vicinity of the slip surface). However, potential strain softening outside the shear zone (i.e. within the embankment) was further investigated through 3-dimensional (3D) numerical modelling, as briefly discussed in the following section. The sheet pile wall was assessed to be subjected to an ultimate bending moment of up to approximately 1,150 kN.m/m and an ultimate shear force of up to 305 kN/m with horizontal movements at the pile head of up to 250 mm. Under such conditions, the sheet pile wall option was considered feasible.

It is important to note that significant simplifications were made to allow assessment using WALLAP. The entire geometry could not be modelled, particularly the section above the sheet pile wall which was simplified to a surcharge as illustrated in Figure 6. Another important limitation of the analysis is that it is based on small strain theory which may be of limited application for large soil movements associated with slope failure. In addition, the methodology adopted assumes that the failed soil mass moves as a rigid body ignoring its own deformation. It was therefore considered that a more sophisticated analysis was required using 3D numerical modelling techniques.

2.2.3 3D numerical modelling of sheet pile wall

In order to address the limitations of the preliminary design stage, a 3D numerical analysis was carried out for the critical section of the embankment, as shown in Figure 5 above, using the commercial Finite Difference computer program FLAC3D.

It is not the intention of this paper to fully describe the numerical analysis. However, the main objective of the numerical analysis was to more accurately model the geometry and loading conditions of the problem, to account for strain-softening effects of the soil materials and to assess the effect of large strain deformation on the sheet pile structural elements.

A Shear Strength Reduction (SSR) technique was adopted to confirm that the sheet pile wall induces the path of least resistance against slope failure to be downslope of the embankment similar to the limit equilibrium approach shown in Figure 5. The model was then allowed to fail under large displacements as shown in Figure 7.

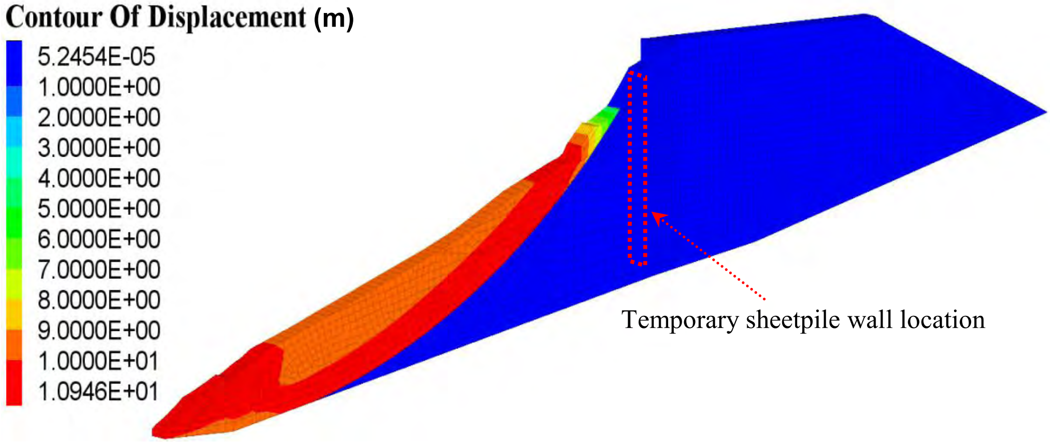

Figure 7: Large scale slope failure.

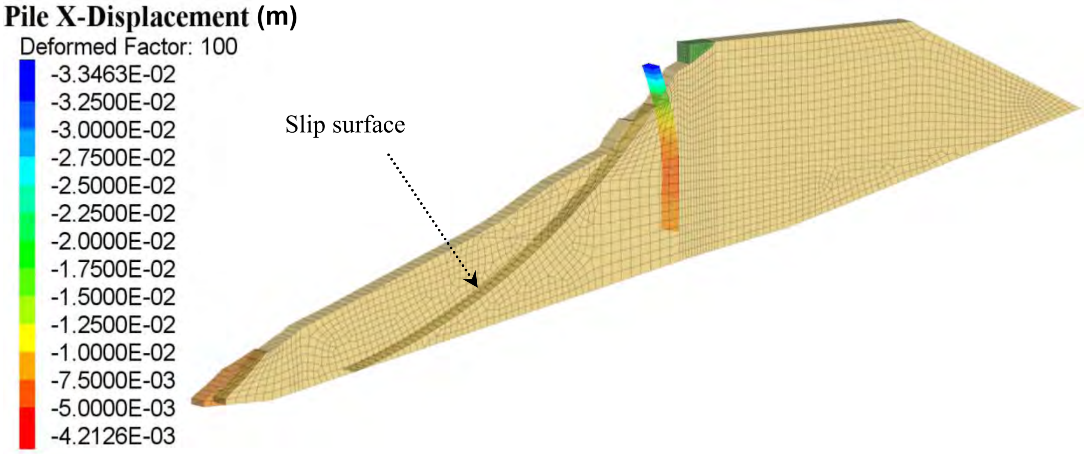

Figure 8: Sheet pile wall deflections after large scale failure (piles exaggerated 100x).

A total displacement of up to 11 m is estimated for the failed soil mass (Figure 7) which reaches equilibrium at a slope angle similar to that assessed using the method after (Khalili *et al.*, 1996). Movements of up to 95 mm horizontal and 100 mm vertical were assessed at the carriageway level as a result of the large scale slope failure when the sheet pile wall is in place. If the sheet pile wall is not installed, collapse of the carriageway occurs upon the same large scale slope failure. This modelling outcome clearly indicated the benefits of the temporary measure in controlling the displacements at highway level.

The 3D model indicated that progressive erosion and loosening could cause the development of a cantilever length within the upper 3 m of the sheet pile wall, in contrast to the 6.5 m high cantilever assessed in preliminary analysis. This scenario was then induced in later stage of the 3D model by removal of the upper 3 m of material in front of the sheet piles. An additional 28 mm of horizontal displacement and 23 mm of vertical displacement were estimated at the carriageway level as a result of this progressive failure.

Although the 3D model indicated the formation of a 3 m cantilever height for the sheet pile wall after downslope failure, an unlikely extreme event was considered that would result in a total cantilever length of 6.5 m, consistent with the analytical preliminary assessment. Under such conditions, large movements were estimated from the 3D analysis. These movements were larger than those estimated by the analytical method possibly due to the large strain approach of the numerical model which increases the bending of the sheet pile wall. Settlement of up to 650 mm was observed at the carriageway level with horizontal displacements of up to 800 mm. These movements indicate a potential collapse of the carriageway with the sheet pile wall yielding, however it is important to note that this condition was assessed to be an extreme event and these movements would be expected to be slow and would still allow enough time for emergency responses to be actioned.

2.2.4 Risk assessment

In order to evaluate the effectiveness of the proposed solution, the RMS ARLs (RTA, 2011) were compared for the two cases, i.e. with and without the remedial measures.

For the condition without the sheet pile wall, different failure mechanisms and associated likelihoods and consequences were considered. The assessed RMS ARLs are presented in Table 1 for the various failure mechanisms. Large scale slope failures typically present low frequency/likelihood with the “Likelihood” rating increasing with decreasing scale of failure. As a result, the likelihood of the different failure mechanisms has been assumed to vary by one order of magnitude between each failure mechanism, commencing with L5 for a large scale failure of 20,000 m^3 as shown in Table 1. The “Vulnerability” rating is a measure of the probability of loss of life resulting from a failure. It is associated with traffic speed as well as the “Failure Mechanism”.

The ARLs for loss of life indicated that for the condition without the sheet pile wall, the assessed risk level would be at ARL3 or worse (i.e. potentially ARL2 when a traffic speed of 100 km/h is considered). The slow lane of the highway is located within the potentially affected failure zone and has traffic volume of approximately 25,000 vehicles per day. The fast lane was more than 7 m from the embankment crest, and was assessed to be outside the immediate zone most likely impacted by a failure of the embankment. This condition resulted in a “Temporal Probability” rating of T1 which is the maximum in the RMS rating. In quantitative terms, however, the “Temporal Probability” would double if the two traffic lanes could be severely affected by a failure. The “Vulnerability” rating is the rating associated with the risk of a fatality given a failure. The “Property Damage and Consequential Effects” rating is the rating associated with damage to the highway given the failure.

The ARLs presented in Table 1 indicate that the existing embankment had a “high” risk.

As discussed above, the sheet pile wall remedial measure targeted to reduce the short term adverse impacts of a large scale failure propagating to the highway, so as to provide sufficient time for monitoring data to be evaluated and the road closed (if required) to reduce the risk of fatality resulting from a failure. As a result, it was considered that the “Likelihood” rating should relate to the movements at the road surface resulting from deflection of the sheet pile wall caused by failure of the embankment downslope of the sheet pile wall. These movements were based on the previous analyses.

The “Likelihood” rating was also based on the assumption that real time monitoring is implemented as part of the temporary measures (which allows for early warning of large movements that may adversely impact road users).

As a result, it was assessed that upon installation of the sheet pile wall and real-time monitoring, an ARL5 could be assigned (Table 2 below) which needs to be continuously revised based on the results of the real-time monitoring. Based on this assessment, the benefits of the construction of short term measures (e.g. installation of a sheet pile wall) including the real time monitoring of the embankment were evident and therefore recommended.

It is important to note that the risk assessment required on-going real time monitoring due to the temporary characteristic of the design which still carried the risk that the highway would have to be closed if adverse conditions were revealed by the monitoring data. This would be similar to a catastrophic event which may not have had on-going monitoring but would require inspections for damage assessment after the event.

The ARLs presented in Table 2 were considered to be applicable only for the temporary condition, up until closure of the highway to traffic in the event of a failure occurring downslope of the temporary sheet pile wall. Should a significant failure of the embankment batter occur there would be loss of lateral support to the sheet pile wall with the slope below the wall being in a meta-stable condition. Progressive failure may then take place due to adverse conditions such as rainfall and erosion. The ARL associated with loss of life is no longer applicable following road closure, and the ARL associated with property damage and consequential effects for some of the mechanisms is likely to become ARL1 following a significant failure. Therefore, the sheet pile wall could not be accepted as a long-term solution nor would be considered a solution to avoid failure under a natural disaster.

Table 1: Risk assessment for condition without sheet pile wall.

Ratings		**Failure Mechanism**			
		Large scale S1 Vol. >20,000 m^3	**Medium scale S2 Vol. >2,000 m^3**	**Small scale S3 Vol. >200 m^3**	**Minor scale S4 Vol. >20 m^3**
Velocity of failure		R5 – very slow	R5 – very slow	R5 – very slow	R5 – very slow
Likelihood(1)		L5	L4	L3	L2
Temporal probability		T1 – heavy urban traffic	T1 – heavy urban traffic	T1 – heavy urban traffic	T1 – heavy urban traffic
Vulnerability (vehicle crossing embankment failure)	Hazard	Deep narrow void	Shallow void (0.2 – 0.5 m step)	Stepped surface (0.1 – 0.2 m steps)	Irregular surface (< 0.1 m steps)
	60 km/h	V2	V3	V4	V5
	100 km/h	V1	V2	V3	V5
Consequence for loss of life	60 km/h	C1	C2	C3	C4
	100 km/h	C1	C1	C2	C4
Assessed Risk Level for loss of life	**60 km/h**	**ARL3**	**ARL3**	**ARL3**	**ARL3**
	100 km/h	**ARL3**	**ARL2**	**ARL2**	**ARL3**
Consequence for Property Damage and Consequential Effects		C1	C1	C2	C2
Assessed Risk Level for Property Damage and Consequential Effects		**ARL3(2)**	**ARL2(2)**	**ARL2(2)**	**ARL1**

Notes:

(1) Relates to the likelihood of failure and resulting movement of the road carriageway

(2) After a significant failure, the ARL associated with property damage and consequential effects for some of the mechanisms is likely to become ARL1.

Table 2: Risk assessment for condition with sheet pile wall.

Ratings		**Failure Mechanism**			
		Large scale S1 Vol. >20,000m^3	**Medium scale S2 Vol. >2,000m^3**	**Small scale S3 Vol. >200m^3**	**Minor scale S4 Vol. >20m^3**
Velocity of failure		R5 – very slow	R5 – very slow	R5 – very slow	R5 – very slow
Likelihood(1)		L5	L5	L5	L5
Temporal probability		T1 – heavy urban traffic	T1 – heavy urban traffic	T1 – heavy urban traffic	T1 – heavy urban traffic
Vulnerability (vehicle crossing embankment failure)	Hazard	Stepped surface (0.1 – 0.2 m steps)	Irregular surface (< 0.1 m steps)	Irregular surface (< 0.1 m steps)	Irregular surface (< 0.1 m steps)
	60 km/h	V5	V5	V5	V5
	100 km/h	V4	V4	V5	V5
Consequence for loss of life	60 km/h	C4	C4	C5	C5
	100 km/h	C3	C3	C4	C4
Assessed Risk Level for loss of life	**60 km/h**	**ARL5(2)**	**ARL5(2)**	**ARL5(2)**	**ARL5(2)**
	100 km/h	**ARL5(2)**	**ARL5(2)**	**ARL5(2)**	**ARL5(2)**
Consequence for Property Damage and Consequential Effects		C1	C1	C2	C2
Assessed Risk Level for Property Damage and Consequential Effects		**ARL3(3)**	**ARL3(3)**	**ARL4(3)**	**ARL4(3)**

Notes:

(1) Relates to likelihood of induced movements on road surface following a failure downslope of the sheetpile wall. The likelihood is dependent on the probability of movement occurring behind the sheetpile wall as well as the probability of failure of the embankment batter downslope of the sheetpile wall, and also the probability that an early warning system installed fails to detect the failure prior to road closure with respect to the risk assessment on loss of life.

(2) These ARLs for loss of life applies only to the temporary condition up to closure of the road (if required) based on the real time monitoring data.

(3) After a significant failure downslope of the sheetpile wall, the ARL associated with property damage and consequential effects for some of the mechanisms is likely to become ARL1

4 CONCLUSIONS

Sustainable and resilient geotechnical designs call for a different thinking from engineers that moves away from the traditional design approaches where nothing is allowed to physically fail.

In order to achieve this objective it is necessary that the primary focus of any geotechnical design is to get the basics right and only then apply the correct use of standards or codes of practice. The combination of strong basic competencies and the need for different thinking will drive engineers to ingenuity. According to Poulos (2014) "ingenuity" does not necessarily mean the application of new or emerging technology, although it may do. The key ingredients are:

- It draws upon multiple and diverse sources (individuals, disciplines, bodies of knowledge) for ideas and inspiration.
- It sees alternative ways to view or define problems and is not constrained by thoughts or approaches of others.
- It combines ideas in unique ways making connections between disparate concepts to deliver results.
- It applies current know how and capability in new and creative ways.
- It meets client's expectations of value which may not necessarily be technically novel.

In addition, risk is part of every human endeavour. As a result, it is essential that the "different thinking" involves not only ingenuity but also intelligent risk taking, i.e. one where the likelihoods and consequences of a potential failure are well understood. A practical example was presented where a risk based approach was adopted and where the solution did not focus on avoiding failure but on managing the risks of a potential failure mechanism by mitigating the likely consequences. With a similar approach, the geotechnical engineer can target reduced disruption to the community and infrastructure that can function effectively as quickly as possible after a catastrophic event, thus attaining a resilient design.

5 ACKNOWLEDGEMENTS

The author of this paper would like to acknowledge the important contribution and guidance of Patrick Wong and Frances Badelow through the design example discussed above. Both provide continuous guidance and mentoring to the author. It is also important to acknowledge the assistance and contribution of Daniel Gorman. The author is also thankful to Frances Badelow for her review of this paper.

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