Concept and Design Methodology of Redundancy in Braced Excavations

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ABSTRACT: The conventional design methodology of deep excavation retaining structure generally proceeds elements by elements, consequently, the retaining structures are/may be lack of redundancy. This could lead to catastrophic collapse of retaining system. It is necessary to introduce the concept of redundancy into the design of retaining structure and develop the design methodology based on redundancy. In this paper, redundancy of deep excavation retaining structure is classified into five aspects. Necessity and importance of each aspect are explained. A method to evaluate and quantify the retaining structure redundancy is presented through the analysis of an example. Two typical case histories are studied to reveal the redundancy problems that may exist. Finally, a series of measures are proposed to increase the redundancy of deep excavation retaining structure.

1. INTRODUCTION

The design of retaining structures generally proceeds element by element; e.g., in a retaining system, namely diaphragm wall, soldier piles, horizontal struts and anchors etc. are designed individually and separately. They are not designed as a robust system; therefore, some retaining systems are/may be lack of redundancy. The adequate safety of the single element is certainly important; however, more important is the safety of the entire structure as a system. So it is necessary to introduce the concept of redundancy into the design of the retaining system of deep excavation and develop the methodology of design to ensure the redundancy of retaining system.

The redundancy in a system is a fundamental tenet of safe design. It's a lesson learned from many catastrophic engineering accidents all over the world, e.g. the Ronan Point apartment building collapse in England in 1968, the Alfred P. Murrah Federal Building collapse caused by terrorist attack in 1995 and the World Trade Center collapse in 2001 (Dusenberry and Juneja 2002), etc. In civil engineering, the redundancy can be recognized as the ability to resist progressive collapse. If one element fails, adjacent elements can take over the function of the failed element. The redundancy theory now has been used in superstructure design. A relatively systematical framework of measures to improve superstructure redundancy has been established (Dusenberry and Juneja 2002, Smith 1988). It is common sense now that important buildings must be designed according to the redundancy theory to restraint progressive collapse, such as National Stadium of China (Bird's Nest) and Guangzhou Tower of China (Shan and Wang 2007).

The safety of excavation in soft soil is increasingly challenging as the depth of the excavation kept increasing, especially when the excavation is conducted at the densely populated area or near various infrastructures. If the excavation collapses, it will lead to disastrous consequences. According to a study of Swiss Federal Institute of Technology, approximately 75% of construction failure cases can be ascribed to human error; while the remaining 25% is attributed to knowingly accepted risks (Ortega 2003). This implies that many specific accidents can possibly be prevented if the human errors were carefully examined before they lead to the failure. However, it is unlikely that all possible human errors or risks can be recognized before the commencement of excavation.

Due to the importance of the deep excavation safety, the concept of redundancy be introduced into the design of deep excavation retaining structure and to develop design methodology is urgently essential. In the design of excavation, the retaining system is expected to be "fail-safe" structure rather than "weakest-link" structure. So for the excavation retaining structure system, the purpose of redundancy design is to make it possible that the retaining system has enough robustness to prevent from progressive collapse, or at least, has ductile behaviour before collapse induced by the damage of localized retaining structure element, which is caused by occasional accidents or human errors.

Osterberg (1989) systematically recommended the necessary redundancy in Geotechnical Engineering. It might be the first time the concept of redundancy was formally used and put forward in geotechnical engineering. Osterberg concerned the redundancy mainly from the philosophy aspect - a way of thinking how we can reduce the chances of failure through the whole phases of the geotechnical structure construction, consisting of reconnaissance and preliminary exploration, soil borings, laboratory testing, analysis, design and construction. He also presented some general principles that should be followed in the design process. It is no doubt that Osterberg's concept is significant and useful for all geotechnical engineers, but few specific measures have been raised by Osterberg and other researchers later on. This paper aims to develop the framework of redundancy in the excavation supporting system design. Some typical case histories are analyzed in terms of redundancy. Finally, the concept of redundancy in deep excavation is clarified and measures that can improve the redundancy of retaining structures are presented.

2. DIFFERENT ASPECTS OF REDUNDANCY IN DEEP EXCAVATION

The retaining system of excavation consists of three parts: the vertical retaining structure (e.g. soldier pile, diaphragm wall and gravity retaining wall), the horizontal bracing structure (e.g. steel strut, RC braced frame, anchor) and the vertical supporting structure of the horizontal bracing (e.g. steel lattice column). Each part has a significant influence on the redundancy of the overall retaining system. For the most commonly used construction methods, namely bottom up method and top down method, the redundancy of an excavation support system could be mainly classified into five aspects as follows.

2.1 Deformation redundancy of horizontal bracing system

The horizontal struts should be arranged to make sure that each connection point between the vertical and horizontal retaining structure has approximately identical stiffness. And if some members of horizontal bracing system don't have enough strength or stiffness, the system can transfer the load of these areas to adjacent structures, so that the local deformation of the weak points will be controlled.

2.2 Stability redundancy of horizontal bracing system

2.2.1 Redundancy of single-level horizontal bracing system

There are a few requirements should be satisfied in the design of important excavation to avoid the progressive failure of the overall retaining system. Firstly, when a local main element is weakened or even fails, there should be alternative load-transfer path. Secondly, the local excessive load (e.g. excessive construction load, surcharge load and traffic load) can be transferred to adjacent retaining structure to avoid localized collapse. For instance, when the cut and cover tunnel is cross-lot supported by steel pipe struts, the combined struts (e.g. truss made by combination of two parallel struts) at a certain interval can be used to prevent the progressive damage of horizontal struts induced by the breakage of one strut.

2.2.2 Redundancy of multi-level horizontal bracing system

When the horizontal bracing system consists of several levels, if a certain level bracing structure collapse or are not installed timely, other levels of bracing structure should have the ability to prevent or at least delay the collapse of the vertical retaining structure and the overall system. This ability is the necessary redundancy of the important excavation engineering.

2.2.3 Redundancy of connection joints of the vertical and horizontal retaining structure

The connection joints should have sufficient strength and ductility; this is important for the integrity of the whole system. If the joint have enough redundancy, it would not break, slip or separate when the strut is subjected to but not beyond a certain amount of excessive pressure or tension.

2.3 Deformation redundancy of vertical retaining system

The deformation redundancy of vertical retaining system is the ability for one specific vertical retaining wall element to transfer the excessive load acting on it to an adjacent vertical retaining wall element to avoid localized large deformation caused by extremely large load, poor quality of soil or over excavation and so on. For example, when the plane form of excavation is concave, the load transfer ability is better because of space effect of retaining structure. But, on the contrary, if the plane form is convex, the local load cannot transfer to neighbouring supporting structure effectively. This means that the vertical retaining system of convex excavation is short of deformation redundancy. On this occasion, reinforced wale will be needed to improve the horizontal continuity and deformation redundancy of vertical structure, and the horizontal struts must be designed with much higher strength too.

2.4 Stability redundancy of vertical retaining system

The stability redundancy of vertical retaining system is the ability for one specific retaining wall element to transfer the excessive load acting on it to an adjacent vertical wall element to avoid failure of local vertical structure caused by extremely large load, poor quality of soil, over excavation, insufficient strength or embedded depth of local vertical structure and so on. Obviously, diaphragm wall, especially with rigid joint, has higher stability redundancy than soldier piles relatively.

2.5 Redundancy of the vertical supporting structures

The redundancy of the vertical column of the horizontal bracing structures is consisted of the redundancy of strength, deformation and stability of horizontal bracing structures. For instance, in soft soil area, the vertical column might suffer following problems:

(1) When the excavation depths of different zones vary greatly, the vertical column located near the zone edge may be subjected to excessive horizontal load.
(2) The base heave of deep excavation can result in additional axial force in vertical columns restrained by horizontal struts.
(3) The vertical columns are also facing the danger of the knock of excavators or other construction machines.

The above risks all can lead to the collapse of vertical columns one after another, so necessary redundancy of the vertical column is needed.

3. HORIZONTAL BRACING SYSTEM REDUNDANCY ANALYSIS

3.1 Internal forces distribution due to element failure

The configuration of system elements of horizontal bracing system can significantly affect the internal forces distribution. Figure 1 shows two ring beam and radial support systems with and without corner bracing. In the following sections, they are referred as *no-corner bracing system* and *corner bracing system* for short, respectively. The two systems are both made by reinforced concrete. The detailed designs of the two bracing systems are summarized in Table 1. Considering the characteristics of horizontal bracing system, the analysis is conducted based on following assumptions.

(1) The material is elastic. The Young's modulus E is 2.8×10^{10}Pa. The compressive strength of concrete is 1.19×10^{7}Pa.
(2) The connections of each element are assumed to be rigid joints.
(3) Plane condition is assumed for the supporting system, so the self-weight of structure is not taken into account.
(4) The ultimate strengths of ring beams, radial bracing and corner bracing are controlled by the compressive strength of concrete with the compressive strength of steel bars neglected. They are calculated by the compressive strength of concrete multiplying the section area of elements. This is because these elements are mainly subjected to axial load and the steel bars are bearing relatively small axial load.
(5) The ultimate strength of wale is controlled by the moment strength. The ultimate moments of the wales of the two systems are identical, both are assumed to be 4116 kN•m.

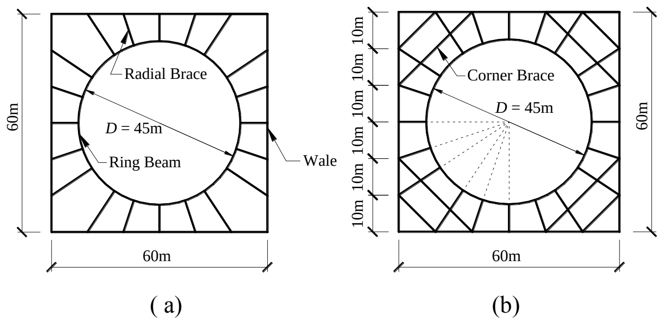


Figure 1 Two horizontal bracing systems: (a) Ring beam and radial support system without corner bracing; (b) Ring beam and radial support system with corner bracing

Table 1 Cross section dimension of each member and the total concrete amount of each design

Design number	Design type	Wale /m^2	Ring Beam /m^2	Radial bracing /m^2	Corner bracing /m^2	Total amount of concrete /m^3
1	No-corner bracing system	1.2×0.6	1.5×0.6	0.5×0.6		363.4
2	Corner bracing system	1.2×0.6	0.8×0.6	0.4×0.6	0.8×0.6	372.8

Note: 1.2×0.6 is the width by the height of the member section.

Table 2 Maximum forces of different types of elements subjected to distributed load of 300kN/m

	Axial force of wale /kN	Moment of Wale /kN•m	Axial force of ring beam /kN	Axial force of radial bracing /kN	Axial force of corner bracing /kN
No-corner bracing system	1758 (8568)	4054 (4116)	10240 (10710)	3308 (3570)	
Corner bracing system	4025 (8568)	4116 (4116)	5159 (5712)	2177 (2856)	3585 (5712)

Note: The values in brackets are the ultimate strengths.

Figure 2 illustrates the distribution of axial forces when the systems are subjected to distributed load of 300kN/m at the peripheral wales, and the maximum forces of different types of elements are shown in Table 2. The ultimate bearing capacities of two systems are nearly identical both are 300kN/m. since the total volumes of concrete are nearly the same, so the two systems may have similar cost.

It can be seen from Figure 2, where the width of each line indicates the comparative magnitude of internal axial force in each element, that the internal forces of corner bracing system are more uniform than no-corner bracing system. There is only one load path for the no-corner bracing system, i.e. radial bracing – ring beam. The axial force of ring beam of no-corner bracing system is extremely large. It undertakes almost total load of the system. So the ring beam is vital to the stability of the overall system and is apparently the key element. On the contrary, the corner bracing system has more load paths, e.g. radial bracing – ring, wale – the longer corner bracing and wale – the shorter corner bracing, etc. Key elements are not obvious for the corner bracing system.

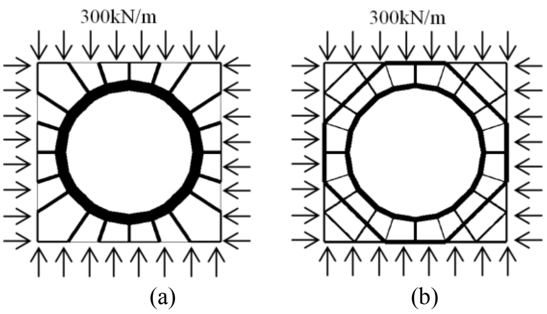


Figure 2 Distribution of axial forces: (a) No-corner bracing system (maximum 10240kN); (b) Corner bracing system (maximum 5159kN)

3.2 Comparison of bearing capacities and failure scenarios

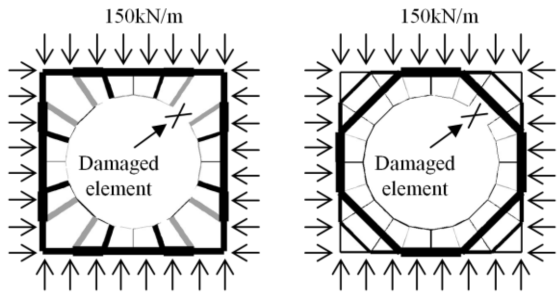
The configuration of system elements of horizontal bracing system can also significantly affect the failure of horizontal bracing system. Some elements of the retaining structure may be damaged due to low quality of construction, mechanical impact or other occasional accidents. The failure of a member could cause the redistribution of load. The redistribution mainly depends on the configuration of system elements and the nature of the member failure (Bennett and Ang 1986). If the redundancy of the overall system is not adequate, other members of the system cannot take the released load by the damaged member and would fail, and then the whole system would collapse. Alternative path method (Smith 1988; Dusenberry & Juneja 2002) can be used to check whether the structure has an alternative load-carrying path and to find out the key elements. In this method, it is first assumed that a certain member of the structure is damaged, then, the capacity and damage degree of the residual structure is evaluated.

The two systems, i.e., no-corner bracing system and corner bracing system, have the same overall ultimate intact strength, i.e., the ultimate load they can take is the same, which is 300kN/m along the wales. By taking the factor of safety of overall system as 2, the working load the two types of system are sustained as 150kN/m. In order to illustrate how the damaged member influences the whole system performance, alternative path method is adopted to implement the analysis. The failure control criterion of each type of components is showed in Table 2. The values in brackets in Table 2 are the ultimate capacity of each corresponding element.

To compare the redundancy of the two types of horizontal bracing systems, a segment of ring beam in both of the two systems is assumed to fail and cannot bear the axial force in ring beam anymore. Figure 3 illustrates the location of damaged members and the redistributions of axial forces of the two local damaged systems under the working load of 150kN/m are shown in Figure 4.

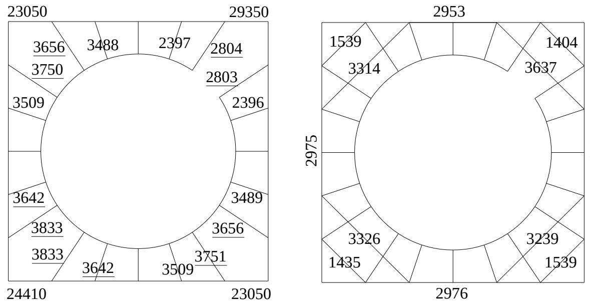
As illustrated in Figure 3a, the axial force of ring beam is much smaller compared with that in Figure 2, it means that the redistribution of internal forces due to the failure of specified ring beam segment is significant. The ring beam can hardly take any load anymore. As shown in Figure 4a, most of the elements are taking the internal forces much beyond their corresponding ultimate capacity; some elements are even subjected to quite large tension. Consequently, the redistribution of internal forces will lead to further failure of more elements till the overall failure of horizontal bracing system. However, it can be seen for Figure 3b that ring beam also can hardly take any load. The internal axial force it took is transfer to the wale and corner beam, which form two alternative load-carrying paths, i.e., wale – the longer corner bracing and wale – the shorter corner bracing. Both of the two paths can undertake the load effectively. Consequently, as shown in Figure 4b, all members can survive after the damage of a member.

In general, when the local damage illustrated in Figure 3 occurs, the no-corner bracing system subjected to working load will collapse while the corner bracing system can remain safe. So the corner bracing system can be classified as “fail-safe” structure. Its redundancy is much higher than the no-corner bracing system.



(a) (b)

Figure 3 Locations of damaged elements and the distributions of axial forces when an element is damaged (black represents pressure while gray represents tension): (a) No-corner bracing system; (b) Corner bracing system



(a) (b)

Figure 4 Some values of internal forces when a member is damaged (the values of wale are moments (kN•m) while others are axial forces (kN), and values with underline represent tension): (a) No-corner bracing system; (b) Corner bracing system

3.3 Method to evaluate the strength redundancy

A number of definitions of redundancy are proposed by Frangopol and Curley (1987) based on ultimate strength, residual strength, and intact strength of structure. These definitions include: (1) the degree of indeterminacy, R_1, (2) the reserve redundant factor, R_2, which is the ratio of ultimate strength (collapse load) of the intact (undamaged) structure to nominal applied load on this system, (3) the residual redundant factor, R_3, which is the ratio of ultimate strength of damaged structural to ultimate strength of the intact structure, (4) the strength redundant factor, R_4, which is defined as

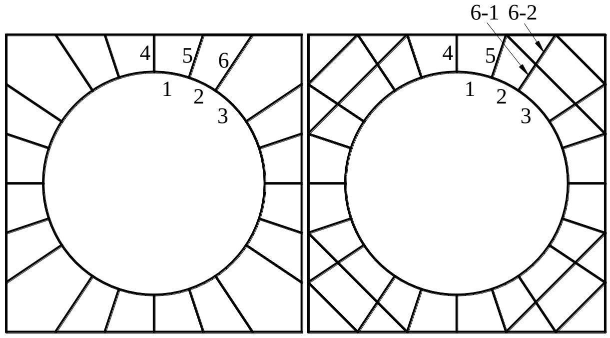
$$R_4 = \frac{L_{\text{intact}}}{L_{\text{intact}} - L_{\text{damage}}} \quad (1)$$

where L_{intact} = ultimate strength (collapse load) of the intact (undamaged) structure; and L_{damaged} = ultimate strength of damaged structural.

The bigger R_4 is, the more redundancy the structure has. When the redundant factor, R_4 is 1.0, it means that damaged element results in the overall system collapse, while an infinity value of R_4 means that the damaged element can only produce negligible effect on the strength of the system. So the failed elements leading to lower redundant factors are important to the system. The damage of these elements may cause catastrophic collapse of the system. Consequently, these elements must be identified as key elements and need additional assurance and inspection of quality.

The structural redundancy should be considered from the standpoints of both member behaviour and overall strength. In these definitions, the degree of indeterminacy R_1 does not constitute an adequate measure of the overall system strength. Other factors R_2, R_3, R_4 certainly are better measures of the overall system strength for intact and damaged structures (Pandey and Barai 1997). Hence, the strength redundant factor, R_4, is adopted in this paper as one of the methods to evaluate the redundancy of the two systems.

The other method adopted is the alternate path method (Smith 1988; Dusenberry & Juneja 2002). Figure 5 shows the numbered element at different positions considering the symmetry of the systems.



(a) (b)

Figure 5 Numbers of elements considering the symmetrical characteristic of systems (a) No-corner bracing system; (b) Corner bracing system

In each case of analysis, only one of the specified elements is assumed to fail. Then corresponding capacity, namely, the maximum load that the system with locally damaged members could sustain, can be obtained, subsequently, the corresponding strength redundant factor, R_4, can be calculated. The capacity and R_4 corresponding to each case, where one of the specified element in Figure 5 is assumed to fail, is summarized in Table 3.

As shown in Table 3, for all cases of no-corner system that there is one of the specified element is assumed to have failed, the ultimate capacity of no-corner bracing system is smaller than the working load applied to the intact bracing system, i.e., 150kN/m. In other words, overall failure will occur for all the no-corner bracing structures. On the contrary, the corner bracing systems except for that when element 1 or element 4 is assumed to have failed can bear higher load than the applied working load. Only the 2 cases that element No. 1 or element 4 fails will lead to the overall failure of corner-bracing system. Accordingly, element No.1 and No.4 can be regarded as key elements of corner bracing system.

Table 3 also shows that the redundant factors of corner bracing system are all much higher than those of no-corner bracing system when the same element is assumed to fail. The lowest redundant factor of all cases could represent the redundancy of the whole system to some extent. The lowest redundant factor of corner bracing system is 1.74, and for no-corner bracing system, the factor is 1.07. The obvious difference indicates that the corner bracing system has more load paths and higher emergency reserve bearing capacity.

3.4 Summaries of the redundancy in horizontal bracing system

By comparing strength redundancy of two horizontal bracing systems qualitatively and quantitatively, some conclusions could be derived as following

(1) The qualitative analysis of the redundancy of a support system could be implemented through the alternative path method. The focus of this method is the redistribution of internal forces and damage behaviour of the system when a certain element has failed.

Table 3 Capacity and R_4 of each type of local damaged system

Number of damaged element	**1**	**2**	**3**	**4**	**5**	**6 (6-1, 6-2)**	
Capacity of no-corner bracing system (kN/m)	25	21	20	146	136	115	
R_4 of no-corner bracing system	1.09	1.07	1.07	1.95	1.83	1.62	
Capacity of corner bracing system (kN/m)	128	150	200	140	270	174	158
R_4 of corner bracing system	1.74	2.00	3.00	1.86	10.00	2.38	2.11

(2) The quantitative analysis of the redundancy of a support system could be conducted using Eq. (1) and the alternative path method. It is verified that the strength redundant factor could evaluate the redundancy of the support system conveniently and effectively.

(3) The no-corner bracing system and the corner bracing system have the same ultimate bearing capacity and cost, however, the redundancy of the former is much lower than that of the latter. This shows that it is necessary to introduce redundancy design into the design of support structure.

(4) The effective alternative load paths are significant to the redundancy of a support system. There are two methods to provide the effective alternative load paths. One is the optimum system configuration, which could provide more load paths of the system. The other is the reasonable element design, which could ensure the efficiency of the alternative path.

(5) The key elements with a low strength redundant factor should be carefully designed and frequently inspected, monitored during construction and service stages.

4. CASE HISTORIES

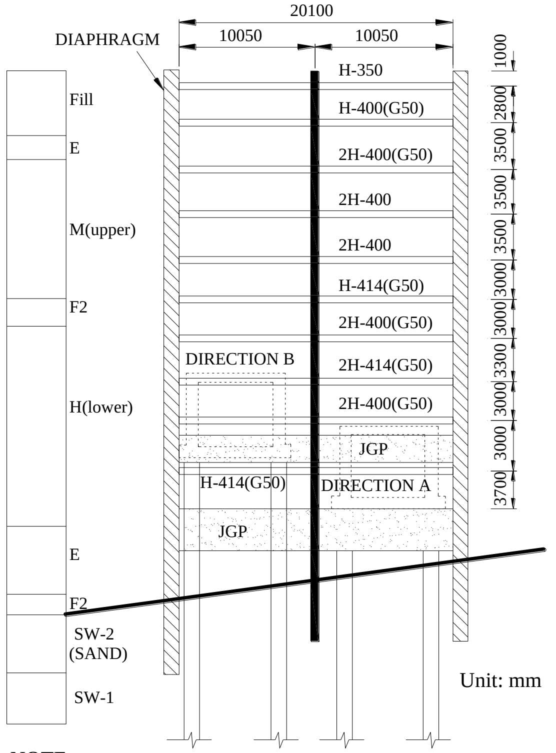
4.1 Nicoll Highway of Singapore MRT circle line lot C824

The collapse area is a part of Singapore MRT circle line lot C824. Figure 6 shows the cross section of the cut and cover tunnel. At approximately 3:30pm on 20th April 2004, the 33m-deep excavation collapsed when excavation reached the 10th strut level. This collapse resulted in four casualties and a delay of part of a US$4.14 billion subway project (Artola 2005). Some utilities including pipe lines and 66kV cable were severely damaged. The Nicoll Highway Station had to move to other position more than 100m away from the collapse area.

In the morning of 20th April 2004, about 8:45, some workers that were preparing to install the 10th level struts heard "thung" sounds, which sounded like something had broken. At round 9:15, when an engineer inspected the work in the tunnel, he found that the inner flange and C-channel stiffener of the 9th level waler had buckled at some positions (COI 2005). After that, more inspection and some meetings were carried out, and some methods that rectify the problem were proposed, e.g. filling the top part of the waler beams with Grade 50 cement, reinforcing waler by placing additional C-channles that were bent and casting a 200mm thick layer of lean concrete at the excavation level. But before these measures were completed, the collapse occurred at 3:30pm (COI 2005). From the time that the yield of the waler at 9th level was found to the total collapse, only 6 hours had passed. It came so fast that there was almost no time to implement the emergency measures.

This collapse proceeded as domino effect. It began from the yield of the strut waler connections at the 9th level, then the 9th level struts failed, following that, the 8th level struts were broken, at last, other levels struts and the whole support system collapsed (Davies 2007). The changes of axial forces of the 8th and 9th level struts could demonstrate the process, as shown in Figure 7 (Davies 2007).

Some research indicated that this accident was caused by several factors, e.g. the misuse of the soil model in diaphragm design (Whittle and Davies 2006), the misuse of the stiff bearing length (approximately 65 mm in accordance with BS5950 was replaced by 400mm mistakenly) in the design of waler (Artola 2005), etc. These two factors lead to that the diaphragm wall suffers excessive deformation and probably cause the strut waler connection undertake higher load than their actual capacity, as shown in Figure 8. In addition to these two reasons, there are three important redundancy problems that caused the sudden collapse.



NOTE:
1. The spacing in the horizontal direction of struts is 4.00 m

Figure 6 Design support system and soil profile for the collapse section (Artola 2005)

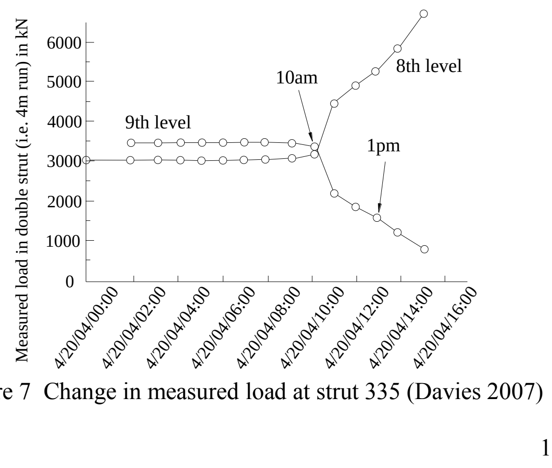


Figure 7 Change in measured load at strut 335 (Davies 2007)

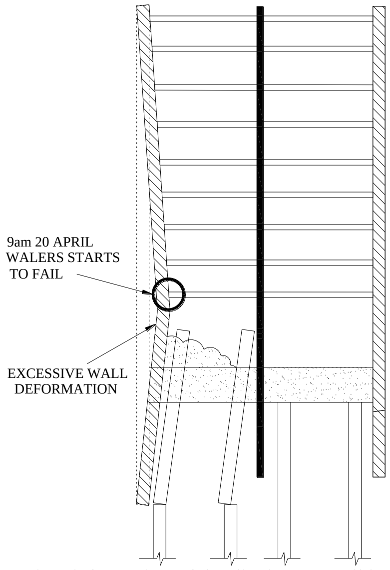


Figure 8 Excessive deformation of the diaphragm wall before collapse

4.1.1 Omission of splays (no alternative load path)

As shown in Figure 9, the struts were originally designed with splays. For the double struts, the splays would take one third of the load in the strut. But a number of struts on the 9th level were not provided splays in the collapse area, as shown in Figure 10. This resulted in that the strut waler connection withstood the 100% load of strut. And additionally, the load paths were reduced and the integrity and robustness of the connection decreased. When the strut waler connection undertook the excessive load, no alternative paths could share the load. So the waler at the connection point yielded and quit working. The connections that failed first were exactly the ones without splays (Artola 2005). Then, other struts must bear the additional load released by the failed struts, which made them collapse too. The progressive collapse began. Supposing the splays were not omitted, the probability of the total failure of the connection would be prevented. So the splays of the connections were not just for strength design, at the same time, they were for redundancy design which could provide more load paths and increase the robustness of the connection.

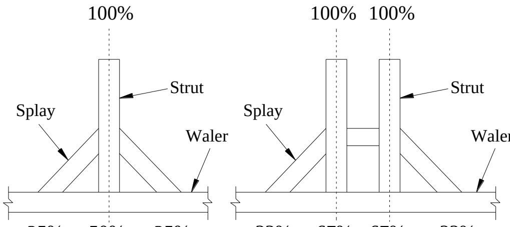


Figure 9 Strut waler connections with splays and the load distribution of the struts and splays (Artola 2005)

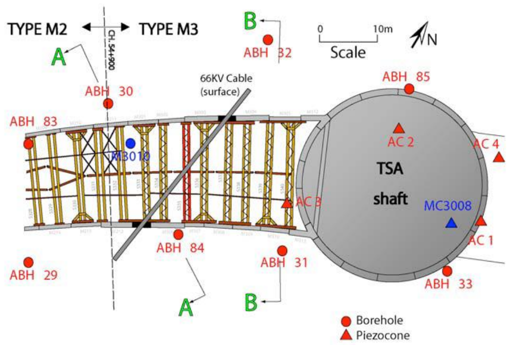


Figure 10 Plan showing location of diaphragm wall panels and 9th level strutting system (Whittle and Davies 2006)

4.1.2 Brittleness of the strut waler connection (lack of ductility)

The ductility has a significant influence on the redundancy of structure (Husain and Tsopelas 2004), and it’s an important aspect of redundancy. In the design of the strut-waler connections from 7th level downwards, double plates were replaced by C-channels as stiffeners without any numerical analysis, model test or field test. In the investigation of the causes of the collapse, some FEM analyses (Cheiw 2006) and model test (Artola 2005) of these two types of connection were carried out. The conclusions of these researches were almost the same. Figure 11 illustrates the load-displacement curves of the C-channel connection and the double plate stiffener connection from laboratory tests.

From Figure 11, it could be found that the replacement of double stiffener plates with C-channel provided only slightly increase of the peak strength of the connection, but this came at the expense of ductility. The load-displacement curve of C-channel connection showed obvious abrupt strain softening after the peak load. This behaviour was due to that the change of C-channel rendered the strut system more susceptible to the brittle “sway” failure mode. When the C-channel was compressed beyond the peak capacity, it was buckled and suddenly released the load acting upon it, resulting in a large reduction of the capacity of the C-channel beyond yield.

The suddenly decrease of the axial load of the 9th level strut in Figure 7 was exactly caused by the brittle response of the C-channel connection beyond peak strength (COI 2005). If the more ductile plate stiffeners were used in all the connections, the collapse would probably have been localized and slower. On this occasion, there would be more time to carry out the emergency measures which could prevent the failure. It can be concluded that improving the ductility of the elements or connections of the system is an effective and crucial way to increase the redundancy of a system.

4.1.3 Low horizontal continuity induced by space effect

As described in the preceding section, when the plane form is convex, the retaining structure has redundancy problem in the horizontal load transferring. Consequently, the deformation of the retaining structure would be relatively large. From Figure 10, it could be seen that the south side of the excavation was convex. The diaphragms walls were constructed by separate panels. Without the continuous wales, the connections of these panels withstood tension because of the space effect, but they were not strong enough to sustain the tension and there were also no alternative path that could undertake the tension. This was one reason that the deformation of the southern diaphragm wall was much larger than that of the northern one (Davies 2007). And the lager deformation promoted the collapse with no doubt. On this occasion, it was better to install reinforced continuous wales and improve the strength of the horizontal struts to improve the redundancy.

4.2 Xianghu station of Hangzhou metro

Xianghu Station was the origin station of Hangzhou Metro Line 1$^{\#}$. The excavation depth and width of this station are approximately 16m and 20.5m, respectively, supported by 800mm thick diaphragm wall and 4 levels of pipe struts (diameter is 609mm and thickness is 16mm). Figure 12 shows the section of the support system and soil profile of the collapse area. At about 3:20pm on 15th November 2008, the western diaphragm wall of the excavation collapsed, and the Fengqing Avenue in the west of the excavation suddenly sank, with the subsidence area of approximately 100m long, 40m wide and 7m deep. After the collapse, the water of the river nearby flowed into the excavation area. This collapse caused 21 casualties and was regarded as the most severe accident in the history of metro construction in China.

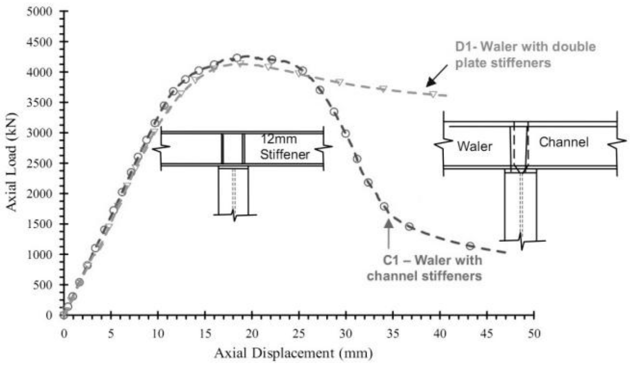


Figure 11 Load-displacement curves of the C-channel connection and the double plate stiffener connection from laboratory tests (Artola 2005)

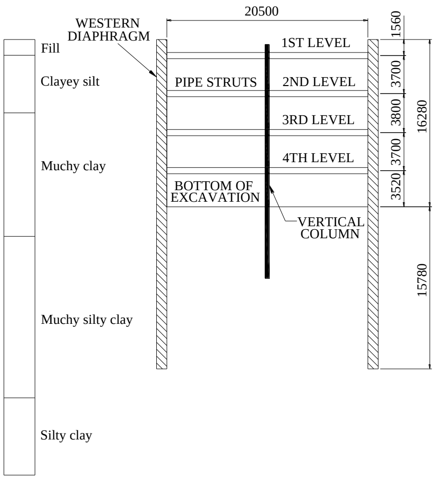


Figure 12 Design section of the support system and soil profile of the collapse area

There are several technical and administrative factors that contributed to this collapse (Zhang and Li 2010). A most important and direct cause is over-excavation. In the collapse area, the excavation proceeded to the bottom when most struts at the 4th level had not been installed. The over-excavation made the diaphragm suffer extremely large shear force at the height of the 3rd level of struts. Furthermore, the western diaphragm wall of the excavation also suffered the excessive vehicle load of the Fengqing Avenue. Consequently, the western diaphragm wall was broken by the shear force at the point below the 3rd level struts induced by the combination of the above-mentioned two factors, as shown in Figure 13. Then the collapse occurred, but if the supporting system had higher redundancy, the collapse would be relatively slower and local. The redundancy problems of the support system were as follows.

4.2.1 Weak connections of the struts and diaphragm

The connections of struts and diaphragm could significantly influence the integrity and robustness of the system. Effective connections could ensure the members of a system to play their roles adequately. Figure 14 shows the messy struts after the collapse. It could be seen that the pipe struts are almost perfect and survived after the collapse, but they are not at their originally installed positions. This indicates that the struts had never undertaken the loads that were beyond their bearing capacity and didn't play a role fully in resisting the collapse.

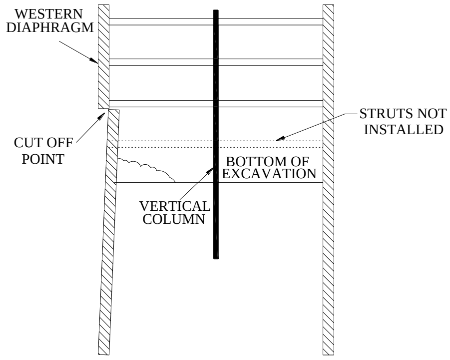


Figure 13 Diaphragms, struts and vertical columns working as an integral frame after a diaphragm was cut off

Figure 14 The messy struts after the collapse

Figure 15 shows that the bracket was two short steel angles welded on the embedded steel plate of the diaphragm. The pipe struts were just put on the brackets without welding or riveting to the diaphragm. When the diaphragm was broken, the load acting upon the struts increased, and what's more, the excessive deformation of the diaphragm wall also made the struts suffer the axial load and transverse load at the same time. But the connections of the struts and the diaphragm could not provide adequate transverse restraint to the struts. Then, the struts at one end slipped away and the other end fell down. This unstable behaviour made the whole system brittle and caused the collapse to happen so suddenly. On the contrary, if the struts were well connected to the diaphragm walls at the both end of strut, the two diaphragm walls, struts and the vertical columns would possibly act as an integral frame in the vertical section of the support system, as shown in Figure 13, therefore, the collapse would be probably mitigated or be more progressive.

Numerical simulation of this collapse with different types of diaphragm-strut connection using PFC 2D was performed by the authors. Figure 16 shows the PFC model of the tunnel when the excavation had reached the bottom and the forth level struts had not been installed. The number of particles in the simulation is about 22000, and the particles near the diaphragm are relatively small to make the analysis more accurate. There are five soil layers in the model, and the micro-properties of particles of each layer are determined through numerical biaxial tests to match the behaviour of intact solid soil (macro-properties) (Itasca, 2002). The diaphragm walls are made by four columns of small particles with contact bonds, and the struts are formed by particles with parallel bonds, which could undertake bending moments.

Figure 15 Brackets of pipe struts

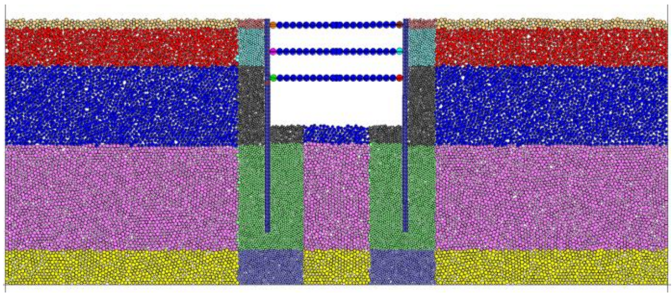


Figure 16 PFC model of Hangzhou metro collapse

When the western diaphragm is broken by shear force, if the struts have not been fixed to the diaphragm tightly and the connection can't bear any shear force or tension, the simulated collapse scenario is shown in Figure 17. It can be seen that the struts fell down for the above mentioned reason and a slip surface was developed subsequently in soil and passed the point where diaphragm wall was broken, which is very similar to the actual situation. For comparison, a model in which the connections of struts and diaphragms are strong enough has also been calculated. Figure 18 shows the scenario when the calculation reaches a relatively equilibrium state, where the struts remain fixed with diaphragm wall at the both ends after the diaphragm wall was broken. Since the struts remained fixed to diaphragm wall at both ends, the horizontal struts would not fall and thus make it possible for the workers on the construction site at the bottom of formation to have more opportunities to evacuate.

Compared Figure 17 with Figure 18, it can be seen that the connection between struts and wale is quite essential to prevent an overall failure of supporting system.

4.2.2 Redundancy of the vertical support system

The redundancy of the vertical support system is vital to maintain the stability of the horizontal struts. Figure 19 shows part of the survived retaining structure. It could be seen that the integrity of the vertical support system of the horizontal struts are not very good. The pipe struts were laid on rather than fixed to the H-beam. This situation could also result in the struts to be more susceptible to fall down. The vertical supporting structure was also not reinforced by the diagonal bracing, which could have made the system to have higher redundancy. Figure 20 illustrates a relative appropriate configuration of the vertical support structure of struts.

4.2.3 Low shear strength of the diaphragm (lack of ductility)

Since that shear failure model is brittle failure, it is very essential for the retaining structure to avoid any shear failure. As mentioned here before, ductility of the elements or connections is significant to the redundancy of a system. But in this case, the diaphragm wall was suffered by the brittle shear failure. This is one of the reasons that caused the diaphragm to collapse in a very short time. There are a lot of advantages of the diaphragm, but its shear strength is low due to the lack of stirrups. Therefore, when diaphragm is adopted as the retaining structure, it is necessary to examine that its shear strength could resist shear failure.

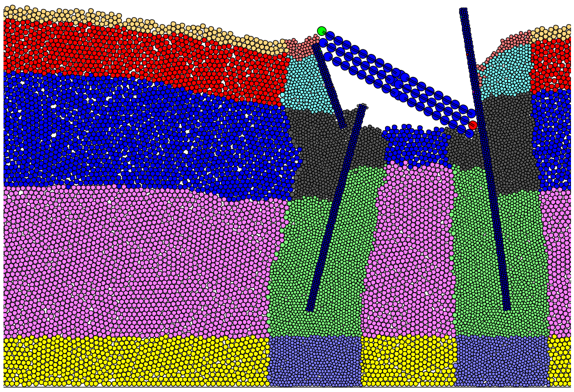


Figure 17 Collapse scenario when the diaphragm-strut connections are weak

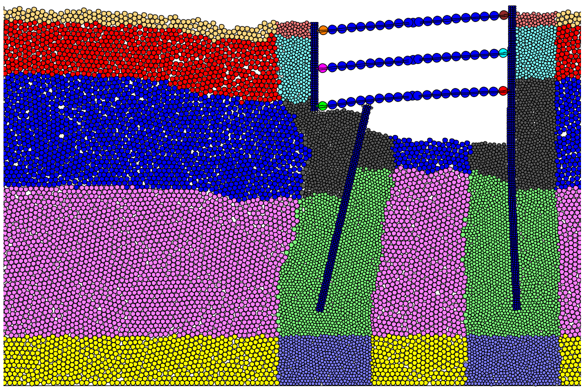


Figure 18 Collapse scenario when the diaphragm-strut connections are strong

Figure 19 Pipe struts and their vertical support structure

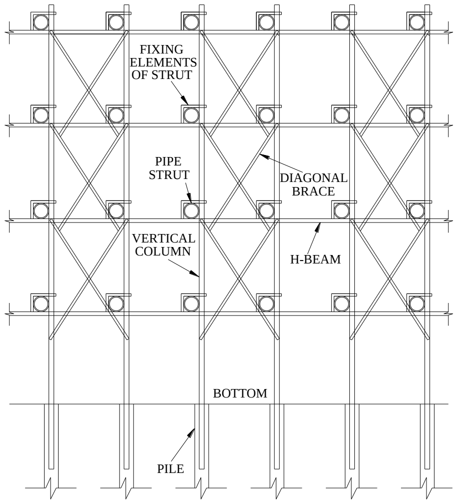


Figure 20 A relative appropriate configuration of the vertical support structure for struts

5. CONCLUSIONS

A lot of lessons have been learnt from some case histories with lack of redundancy that resulted in the retaining system susceptible to brittle overall failure. Thus, it is very important to introduce the concept and methodology of redundancy into the design of retaining structure. A framework of redundancy in deep excavation retaining system is presented as follows:

1. The redundancy of excavation support system consists of five aspects. Each aspect should be considered in the design in order to improve the system redundancy. If the support system has high redundancy, the collapse of the system would be prevented and when occasional local damage occurred, the collapse would be localized or more progressive.
2. A competent design of the retaining system should improve the system redundancy through optimum elements configuration and other construction measures with little or no increase in the construction cost.
3. Alternative path method could be used to judge the redundancy of the excavation support system and determine the key elements. Strength redundant factor could be adopted as a quantitative index to measure the redundancy of the support system.
4. Through the analysis and case studies, the following measures that are significant and effective to improve the support system redundancy are proposed:

   (i) Develop more effective alternate load paths through reasonable arrangement and design of elements.
   (ii) Increase the connection resistance to improve the integrity and robustness of the system.
   (iii) Ensure that the connections and elements have sufficient ductility.
   (iv) Reinforce the support structure at certain interval through diagonal struts or other construction measures to improve the system robustness.
   (v) Install continuous wales to increase the continuity of retaining structure at horizontal direction when the plane form of excavation is convex.
   (vi) Key elements have higher strength and ductility than other elements.

5. Key elements are vital to the stability of retaining system. Design and construction of key elements should be carefully examined and inspected and more importantly, be monitored during excavation.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

Artola, J., (2005) “A solution to the braced excavation collapse in Singapore.” Master thesis, Massachusetts Institute of Technology, Boston, United States of America.

Bennett, R. M. and Ang, A. H., (1986) “Formulations of structural system reliability.” Journal of Engineering Mechanics, 112(11), pp1135-1151.

Cheiw, S. P., (2006) “Behaviour of strut-waler connections with different stiffening details.” The Structural Engineer, 84(14), pp28-31.

COI (2005) “Report of the Committee of Inquiry into the incident at the MRT circle line worksite that led to collapse of Nicoll Highway on 20 April 2004.”, Ministry of Manpower, Singapore.

Davies, R. (2007) “Factors in the Nicoll Highway collapse.” Tunnels & Tunnelling International, Feb, pp31-34.

Dusenberry, D. O. and Juneja, G. (2002) “Review of existing guidelines and provisions related to progressive collapse.” http://www.nibs.org.

Frangopol, D. M. and Curley, J. P., (1987) “Effects of damage and redundancy on structural eliability.” Journal of Structural Engineering., 113(7), pp1533-1549.

Husain, M. and Tsopelas, P., (2004) “Measures of structural redundancy in reinforced concrete buildings. I: redundancy indices.” Journal of Structural Engineering., 130(11), pp1651-1658.

Itasca Consulting Group, Inc.: PFC 2D (Particle flow code in two dimensions) version 3.0; sections: user’s guide, (2002)

Ortega, I. (2003) “Failure prevention in innovative or high-risk construction projects due to procedural redundancy during the design phase.” Forensic Engineering, 241(48), pp485-494.

Osterberg, J. O., (1989) “Necessary redundancy in geotechnical engineering.” Journal of Geotechnical Engineering, 115(11), pp1513-1531.

Pandey, P. C. and Barai, S.V., (1997) “Structural sensitivity as a measure of redundancy.” Journal of Structural Engineering, 123(3), pp360-364.

Shan, L. and Wang, Y., (2007) “Research of progressive collapse in modern structural engineering.” Industrial construction, Supplement, pp615-623.

Smith, E. M., (1988) “Alternate path analysis of space trusses for progressive collapse.” Journal of Structural Engineering, 114(9), pp1978-1999.

Whittle, A. J. and Davies, R. V., (2006) “Nicoll Highway collapse: evaluation of geotechnical factors affecting design of excavation support system.” International Conference on Deep Excavations, Singapore.

Zhang, K. C. and Li, J. M.,(2010) “Accident analysis for ‘08.11.15’ foundation pit collapse of Xianghu Station of Hangzhou metro.” Chinese Journal of Geotechnical Engineering, 32(S1), pp338-342.