Deep Excavation Failures: Can They Be Prevented?

INVEITED LECTURE

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given to

CERTIFICATE OF PRESENTATION AND PARTICIPATION

20 & 21 June 2012 - Bangkok, Thailand

International Symposium on Sustainable Geosynthetics

GREEN TECHNOLOGY FOR CLIMATE CHANGE (SCGC)

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DEEP EXCAVATION FAILURES, CAN THEY BE PREVENTED?

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ABSTRACT

The writer has been working in the field of geotechnical engineering since 1984, along the way he has seen a number of deep excavation failures, some with minor casualties, others involving a huge amount of economic loss, some cost no human life, others with a number of fatalities. This paper tries to discuss what could be the causes of those failures, from the possible technical to the non-technical reasons. It also tries to extract what can be learnt from those failures, starting from the lack of reliable soil investigation data, inadequate geotechnical design knowledge, poor execution, to poor quality control. The non-technical reasons, such as: the lowest bid win policy and its implication are also discussed. Finally, steps to minimize geotechnical failures are suggested.

Keywords: deep excavation, failure, software factor, quality control, lowest bidder win, prevention

INTRODUCTION

A few months ago, in a geotechnical mailing list, there is a simple but challenging question, i.e.: “Geotechnical failures — Do they happen and can we prevent them from happening?” It is a simple question to answer; “Do they happen?”; the answer is very simple, that is: “There were many geotechnical failures, large or small scale, they are facts of life. However, a lot of the failures were unexposed to the outsider, the parties involved usually tried to settle the failures quietly among themselves.” However, to answer: “Can we prevent them from happening?” is a challenging task, as the answer is no longer simple. It needs in depth investigation on the causes of the failures, starting from the soil investigation report, design documentation, execution and supervision of the project, to the non-technical matter that usually initiated from too lower pricing of the project.

The writer, either he gets involved in the project or not, always curious to learn from the geotechnical failures, to search for the project data and to carry out a back analysis. A failure is always a good real life laboratory for engineers to learn and to get more insight on the geotechnical problems and to enhance our knowledge. This paper gives examples on the geotechnical failures, especially deep excavation failures, discusses the possible technical and non-technical causes of the failures, and finally closing the paper with recommended steps that can be taken to prevent future failures.

DEEP EXCAVATION FAILURES CASES

Inadequate stability analysis of an open cut excavation, often executed for basement constructions, can lead to a slope failure which in turn causing driven piles that had been put into place were subjected to large lateral force that lead to the failure of the piles (Fig. 1). The consequence of such a failure in a building foundation, new piles have to be reconstructed.

Insufficient toe penetration of steel sheet piles, would lead to excessive movement of the sheet piles toe, which often lead to kick in failure. This kick in failure would then lead to large and often sudden sagging of the ground behind the wall (Fig. 2). If this event were to take place near adjacent buildings and utilities, the buildings and utilities would have had collapse.

The earth pressure induced by soft clay was often wrongly calculated, as a result, a cantilever sheet piles wall systems was in total failure (Fig.3a) causing the adjacent road to collapse and traffics were severely interrupted. Further lateral movement of the soft soils was tried to be stopped by installing 60cm diameter soldier pipe piles (Fig.3b). The pipes were also casted with concrete, but it was NOT successful. Figure 3c shows that the pipe piles were eventually slanted to almost 30 degrees. One must understood that once the soil movement exceeds their yield stresses, it will be very difficult to stop further movement.
Fig. 1 Failure of open cut excavation that lead to driven pile foundation failures - North Jakarta - 2005

Fig. 2 Kick in failure of sheet pile – Surabaya - 2007
Fig. 3  Failure of sheet pile walls; further soil movement was tried to be stopped by soldier pipe piles but failed – West Jakarta 1995

All the previous examples of failures were taken place at very soft to soft gray to black clay. However, failure of retaining walls can also occur at relatively strong, medium to stiff clays shown in Figure 4. With 16m depth excavation, since the soil layer from 9m below was cemented sand with SPT blow count as high as 60, the engineer decided to retain the upper 9m of soil by installing 40cm diameter soldier driven piles up to 9m depth with center to center distance of 1.25m. The system was proved inadequate. The upper 9 m of the soil collapsed (Fig. 4a), the capping beam and the soldier piles moved excessively and broken (Figs. 4b and 4c).

Figure 5 shows a “careless” open cut excavation led to the collapse of a 13 stories building in China. In Indonesia, in 1990-91, a similar excavation occurrence, combined with ignorance in anticipating the effect of Franks piles construction nearby an adjacent building, together with the incapability of interpreting flawed pile loading tests had caused a 9 story building to severely tilted. Finally, the building was deemed unusable and had to be totally destroyed.

April 21, 2004 a serious incident of excavation failure took place in Singapore, a country with stringent construction rules (Fig. 6). The failure had caused the loss of four lives, the collapse of pedestrian bridge, and the total cut off of a major highway, namely Nicoll highway. The project was a cut and cover excavation for an underground MRT (Mass Rapid Transit). The excavation was 33-34m deep, protected with 44.3m depth diaphragm wall along its two sides. Steel beams spanning from one side of the wall to the other side were installed as strutting/shoring system.

TECHNICAL ISSUES THAT CAN LEAD TO FAILURES

Based on the failure cases investigated, the author summarized the possible technical issues that often forgotten or ignored or wrongly calculated, in the design stage and in the execution phases, starting from the simple equation of earth pressure theory to the implementation of sophisticated finite element software.
Fig. 4  Failure of small diameter soldier (driven) piles. The capping beam and the soldier piles moved excessively and broken – South Jakarta – 2004.
Fig. 5 Ignorance open cut excavation led to a building collapse, China – 2010
Cohesion Factor in the Earth Pressure Formula

In the calculation of the lateral earth pressures acting on a retaining wall system, the engineers generally know the following formula:

\[ P_{a}' = k_a \sigma_v - 2c' \sqrt{k_a} \]  \hspace{1cm} (1)

\[ P_{p}' = k_p \sigma_v + 2c' \sqrt{k_p} \]  \hspace{1cm} (2)

where:  
- \( P_{a}' \) = active earth pressure,  
- \( P_{p}' \) = passive earth pressure,  
- \( k_a \) = active earth pressure coefficient,  
- \( k_p \) = passive earth pressure coefficient,  
- \( \sigma_v \) = effective overburden pressure, and  
- \( c' \) = drained cohesion.

The \( c' \) value in the above formula reduces the active earth pressure, on the other hand it increases the passive earth pressure, hence, over estimating \( c' \) will lead to unsafe condition. One has to understand that in soft normally consolidated soils, \( c' \approx 0 \), and even if the triaxial test results show the existence of \( c' \), which is normally the case of unsaturated samples, it is suggested to take \( c' = 0 \).

In total stress analysis where the undrained cohesion \( c_u \) prevailed, the \( k_a \) and \( k_p \) values for soft clay is equal to one, because the undrained internal angle of friction, \( \phi_u \), is zero. Note that soil investigation reports often show \( \phi_u = 0 \), this happened because the samples tested were not in a fully saturated condition; the water content somehow had reduced during the preparation or the keeping of the soil samples, whereas in situ soft soils are generally in a fully saturated condition.
One another factor that need to be understood is: for deep excavation, the passive earth pressure calculated by Coulomb theory shall be overestimated. It is suggested to use the passive earth pressure coefficient derived by Caquot and Kerisel (see Gouw, 2009).

If prestressed ground anchors or prestressed strutting are used, the earth pressure coefficient k shall moves back and forth within the values of k, and k_p.

**Water Pressures**

Fluctuation of ground water tables must be investigated. In area where rain intensity is high, the difference within the rainy and dry season can be of several meters. When excavation is executed near a river or sea shore, the influence of high and low tides to the ground water table also need to be investigated. Failure in estimating the ground water tables shall lead to the wrong calculation of water pressures acting on the retaining walls, and it can contribute to excessive movement of the retaining wall. In an adverse condition may also cause failure.

Observation of ground water table through soil investigation boreholes only is inadequate. It can lead to wrong elevation of the ground water table. The proper measurement should be done by installing observation wells and piezometers. Best installed in every significant layer of soils. The measurement should span over the rainy and dry season. By employing this method, the correct water table during the dry and rainy season can be identified. The existence of artesian water pressure, if any, can also be identified. The measurement issues of the ground water table is elaborated in detail by the author in the papers titled “Pumping Test and Its Interpretation for Dewatering Purposes” (Gouw, 1994); “Dewatering” (Gouw, 2010).

When excavation is conducted near sources of water, such as: river, lake, reservoir, etc., the possibility of water seepage into the excavation area must be explored.

**Seepage Force**

Seepage of ground water toward the excavated area is often forgotten in analyzing the stability of earth retaining structure. The mode of the seepage depends on whether water can pass through the retaining wall or not.

For open cut excavations and retaining wall systems where water can seep/flow through the wall, e.g. soldier piles, the stability of the excavation shall be seriously impaired if ground water is allowed to flow through the slopes or the walls. Therefore, it is very important to prevent the ground water to flow out from the slope of the open cut excavations or through the walls of the retaining wall system. For that it is advisable to install dewatering wells at the perimeter of the excavation area (Fig. 7).

For an excavation with impervious retaining walls, e.g. diaphragm walls or secant piles, where the toe of the walls is located in a permeable soil layer, then the walls will not act as a water cut-off system. This means, water can seep from outside the walls into the excavation area through the permeable soil layer below the walls’ toe as shown in Fig. 8. This ground water seepage creates seepage force which increases the effective overburden pressure in the active side of the walls, and on the other hand, reduces the effective stress in the passive side of the walls. This means the seepage force increases the lateral pressure to the walls and decreases the passive pressure. A large seepage force may significantly reduce the effective overburden pressure and subsequently will induce piping and boiling. This effect of seepage force is often forgotten by inexperienced design engineers and contractors.

If the retaining wall is embedded into an impermeable layer (Fig. 9), there will be unbalance water pressure within the active and passive sides. When the base of an excavation is impermeable, say by jet grouting a layer at the base of the excavation, the base of the excavation is then subjected to an uplifting force (Fig. 10). Therefore, to withstand this uplifting force, the thickness of the base has to be calculated. Ignorance in calculating this uplifting force can cause failure.

**Artesian Water Pressure**

The existence of artesian water pressure can greatly affect the stability of an excavation. The weight of the soil from the excavation level to the top of the aquifer layer and the friction of the soil-wall system should be able to withstand the artesian pressure (Fig. 11); otherwise the base of the excavation shall fail. This type of failure is known as bursting or boiling. In a smaller scale, the seepage of the artesian water reduces the passive resistance of the soil. Undetected artesian water pressure beneath an excavation may lead to unsafe excavation.

**Squeezing / Soil Flow**

When soldier piles system is used as retaining structures for soft soils, soil squeezing or soil flow through the gaps within the soldier piles may take place (Fig. 12). This phenomenon may affect the stability of the structures/facilities adjacent to the excavation area. Therefore, it should be noted that the gaps within the soldier piles must be close enough to ensure the formation of arching (arching effect) where the soft soils could not penetrate or squeeze out of the gaps.
Fig. 7 Ground water seepage through soldier piles.

Fig. 8 Groundwater seepage through impervious wall

Fig. 9 Unbalance water pressure

Fig. 10 Impermeable layer at base

Fig. 11 Artesian water pressure
Heaving

For braced excavation system, it is quite common that the design engineer forget to take into account the heaving mode of failure. This mode of failure can take place due to the weight of the soil columns, of 0.7 excavation width, at the sides of the excavation pushing inward from the bottom of the excavated area. If the bearing capacity of the soil beneath the excavation area is unable to withstand the soil column weight, then heaving failure can take place (Fig. 13).

Geotechnical Software

The advance of computer technology, made personal computers no longer a luxury item, it even becomes a necessity. Every consultant, contractor, and even almost every household have computers. However, one of the negative side effect is many peoples relied too much on the computer software. It is quite common engineers believe that the output obtained from geotechnical software calculation is an accurate solution for their problems at hand, especially to those engineers with inadequate knowledge and lack of experience in designing geotechnical works. In order to save cost, the contractors and consultants who owned sophisticated geotechnical software such as: PLAXIS, CRISP, SIGMA, FREW, WALLAP, MIDAS, etc., felt that with those advance software they no longer need to consult geotechnical expert or geotechnical specialist. Realizing it or not, they believe the engineers they sent to attend the geotechnical software short courses are capable enough to design a geotechnical structures. They forgot the adage in computer application, that is: Garbage In Garbage Out. What is the garbage then?

- **Wrong Application of Soil Model**: There are many soil models available for geotechnical analysis, e.g.: Mohr-Coulomb Model (elasto-plastic model), Soft Soil Model (soft soil, soil creep, and critical state soil models), Hardening Soil Model (hyperbolic soil model), etc. Each of the soil models have its own weakness, strength and suitability to be applied to a particular problem. Choosing the wrong soil model may lead to wrong estimation on the performance of the geotechnical structure. Mohr Coulomb Model is the most common method.
adopted. It is a simplification of non-linear soil behavior into bilinear soil model. This model does neither include stress-dependency nor stress-path dependency of soil stiffness. Generally, speaking, when the safety factor in the design is taken to be less than two, the output of this calculation type is less reliable. Hardening Soil Model (Hyperbolic Soil Model) incorporates the loading history of the soil and strain depended stiffness, however it does not take into account the softening due to dilatancy. This model is good for excavation problem. Soft Soil Model is good for the application of the situations dominated by compression. It is not recommended for excavation problems.

- **Wrong Adoption of Soil Parameters:** Use of drained shear strength for undrained condition and vice-versa. Wrong adoption of shear strength parameters. Wrong determination of soil stiffness. Over estimation of those values can lead to dangerous situation.

- **Wrong Modeling of Undrained Condition in Mohr-Coulomb Soil Model:** It has to be noted that in Finite Element Software (PLAXIS for examples), there are three methods to model the undrained behavior (see Fig. 14).

**Method A (analysis in terms of effective stresses):**
- type of material behaviour: undrained
- effective strength parameters $c', \phi', \psi'$
- effective stiffness parameters $G_{eq}, \nu$

**Method B (analysis in terms of effective stresses):**
- type of material behaviour: undrained
- undrained strength parameters $c = c_u, \phi = 0, \psi = 0$
- effective stiffness parameters $G_{eq}, \nu$

**Method C (analysis in terms of total stresses):**
- type of material behaviour: nonporous or drained
- total strength parameters $c = c_u, \phi = 0, \psi = 0$
- undrained stiffness parameters $G_{eq}, \nu = 0.495$

Fig. 14 Three methods for modeling undrained behavior in FEM

Employing method A for undrained analysis in Mohr-Coulomb model leads to overestimation of undrained shear strength as shown in the stress path diagram on Fig. 15. The stress path of Mohr-Coulomb model will be perpendicular to mean effective stress axis ($p'$ axis) until it touched the failure line at an undrained shear strength higher than the real value of $C_u$. This over-estimated $C_u$ can be prevented by adopting method B where the real $C_u$ value is used as input in the program. However, it has to be noted that, either Method A or Method B, both do not follow the stress path of undrained behavior of real soil that curves upward to the left.

**Construction, Supervision, and Monitoring**

The quality of the construction is one of the key factors in assuring the safety of a deep excavation. Good construction method, supervision and monitoring system must be adopted. The design assumption must be clearly stated in the design report and it has to be explained to the contractor. The contractor must pay attention to all the design assumptions, if there is any discrepancies in the field, the contractor must report and carry out coordination with the designer. For example: The embedment depth of retaining wall executed differs greater than the tolerance given by the designer. A shallower embedment depth may provide inadequate fixity. Larger embedment depths may signify the existence of softer layer than predicted by the designer. All this may affect and harm the stability of the retaining structure.

Geotechnical instrumentation must be installed to monitor the lateral movement of the retaining walls, to measure the settlement of the surrounding area, and to monitor the water level in the excavation area as well as outside the retaining walls. Compared the measurements with the predicted values obtained in the design stage. If the values exceed the tolerance given by the designer, the contractor must alert the designer and all the parties involved to carry out the necessary review and action.

**NON TECHNICAL FACTORS**

All the parties involved in the construction industries definitely know the bidding system where the words "lowest bidder wins" are well known. The intention of this type of bidding system is to achieve cost efficiency. However, it also carries the negative side effect, that is: the tender participants will try to cut cost here and there, very often, by sacrificing quality and safety. The participants that lost in one tender would bid lower in the next tender, then the ones lost in this tender will also bid lower in subsequent tenders, and the trend goes on until it reaches unhealthy state where the consultants,
contractors and sub-contractors do not have enough profit margins. The effects of this behavior are lengthy, among others are:

- Consultants cannot pay qualified engineer in a reasonable manner, they do not have enough budget to enhance the knowledge of their engineers; very often they even do not have money to upgrade themselves. Unable to attend good seminar and courses, unable to buy licensed software, not to say to develop research and development department. Low and inadequate income make good engineers seek for other professions. The effect? Of course the soil investigation report and the design quality will be lower and lower. Figure 16 shows low pricing lead to wrong soil investigation report due to lack of proper quality control.

![Grain Size Distribution Curve](image1)

![Mohr Chart CU Test](image2)

**Fig. 16** Wrong soil investigation report due to bad pricing.

- The main contractors shall press sub-contractor pricing, then who will the sub-contractor press? The clear facts are everyone will cut cost here and there. The first stage is trying to cut construction temporary supporting elements (temporary work), for examples: omit the capping beam that tie diaphragm walls panels / soldier piles into one system, omit some waller beams in a strutting or ground anchoring system, reducing the number of struts, cut cost on the dewatering system. When cost cutting is successful in one project, the contractors are getting daring from one project to another. They forgot that the soil condition varies from one place to another. This kind of cost cutting on temporary work which is often take place in the execution of deep excavation, can lead to fatal failure.

One of the causes of the failure on the cut and cover MRT excavation shown in Fig. 6 was the improper strutting system. Figure 17 shows the buckling of the waller stiffener. It can also be seen that the waller was not a continuous beam, therefore, when one segment of the diaphragm wall was subjected to higher force than predicted, the redistribution of load to the adjacent diaphragm wall panels could not take place. Another indirect factor that contributes to the failure was the contract value was too low; the contractor price was way too low compared to its nearest competitor.

Other example of cost cutting on temporary work supports that lead to failure of mat foundation reinforcement fabrication occurred in Singapore on May 2004. At that time the stacks of six layers 32 mm upper reinforcement of the mat foundation collapsed, hitting and causing the loss of life of the workers working underneath the reinforcement (Fig. 18). The collapse of the reinforcement must be due to inadequate vertical supports, and that was due to cost cutting effect. It was a bitter lesson, too much cost cutting lead to fatal failures!

The next effect of unreasonably low cost is the consultants / contractors try to cut overhead. They do not have budget to hire qualified engineers, especially good geotechnical engineers. The consequence is they are unable to see the danger that may take place. Despite the fact that the engineers very often have to work overtime with no compensation at all, the salaries of the engineers are inadequate. While the cost of living increases year by year, the engineers’ salary hardly moves up, sometime they even get reduced salary under the reason of economic crisis. Compared to their peers in the financial world their salary are way too low, therefore, the capable engineers start to seek for another professions that give much better compensation. Of course the scarcity of good and qualified engineers leads to lower quality of construction work. The author had written the exodus of construction engineers to other field of professions in a paper titled “Engineers and Their Problems” (GOUW, 2003).
Fig. 17 Discontinuous waller and the buckling of the stiffener (Richard Magnus, 2005)

Fig. 18 The collapse of mat foundation reinforcement due to inadequate supports

- The saddest thing of all is the engineers that pressure engineers, just merely to follow the instruction of the owners. The engineers that act as a quantity surveyor (QS) often carry out the “price negotiation” with very shallow basis. They collected lowest pricing of every items from every contractors, for examples: A was lower in boring, they took boring price from A; B was lower in concreting work, they took concreting price from B; C was lower in reinforcement price, they took reinforcement price from C; and so on. The QS often does not (and does not want to) understand geotechnical work. They often use the sentences: “Contractor A can do it with this price, why can’t you do it?” They could not see the potential problems of low costs and they do not want to understand what they are negotiating at. Their attitude shows that
they are not qualified to be named QS. Ones do not need an engineer for doing that way of negotiation! A senior high school graduate is enough for carrying out that “wet market” like negotiation! Good QS must understand what he is negotiating at, how to carry out the construction work, want to understand and want to seek and to survey for proper pricing of every item he is negotiating at. He must give feedbacks to the owner on the proper price level, and not only pressing the pricing of the consultants/contractors/sub-contractors.

CLOSURES

The author ever received an email telling a story about ENGINEER vs SALES PEOPLE. The story written by a master degree geotechnical engineer can be a brain storming idea for us to learn more about finance and marketing in order to sell our engineering product and expertise to the economist (owner) with reasonable prices. The story goes like this:

The first...

Eleven people were dangle below a helicopter on a rope. There were ten sales people and one engineer. Since the rope was not strong enough to hold them all, they decided that one of them had to let go to save all the others. They could not decide who should be the volunteer. Finally the engineer said he would go of the rope since engineers are used to do everything for the company. They forsake their family, don’t claim all of their expenses and do a lot of overtime without getting anything in return. When he finished his moving speech all the sales people began to clap...

Moral:
Never underestimate the powers of the engineer.

The second...

A group of engineers and a group of sales people take a train to a conference. Each sales person holds a ticket. But the entire group of engineers has bought only a single ticket. The sales people are just shaking their heads and are secretly pleased that the arrogant engineers will finally get what they deserve.

Suddenly one of the engineers calls out: “The conductor is coming!”. At once, all the engineers jump up and squeeze into one of the toilets. The conductor checks the tickets of the sales people. When he notices that the toilet is occupied he knocks on the door and says: “Ticket, please!” One of the engineers slides the ticket under the doors and the conductor continues merrily on his round.

For the return trip the sales people decide to use the same trick. They buy only one ticket for the entire group but they are baffled as they realize that the engineers didn’t buy any tickets at all. After a while one of the engineers announces again: “The
conductor is coming!’ Immediately all the sales people race to a toilet and lock themselves in.

All the engineers leisurely walk to the other toilet. Before the last engineer enters the toilet he knocks on the toilet occupied by the sales people and says: ‘Ticket, please!’

And the moral of the story?

Sales people like to use the methods of the engineers, but they don’t really understand them.

The third...

Once upon a time three sales people were walking through the woods and suddenly they were standing in front of a huge, wild river. But they desperately had to get to the other side. But how, with such a raging torrent? The first sales guy knelt down and prayed to the Lord: “Lord, please give me the strength to cross this river!”

The Lord gave him long arms and strong legs. Now he could swim across the river. It took him about two hours and he almost drowned several times.

But he was successful!

The second sales guy, who observed this, prayed to the Lord and said: “Lord, please give me the strength and the necessary tools to cross this river!”

The Lord gave him a tub and he managed to cross the river despite the fact that the tub almost capsized a couple of times.

The third sales man who observed all this kneeled down and prayed: “Lord, please give me the strength, the means and the intelligence to cross this river!”

The Lord converted the sales man into an engineer. He took a quick glance on the map, walked a few meters upstream and crossed the bridge.

Send this to an intelligent engineer so that they have something to smile about; and to the sales people if you think they can stomach the truth!

The above story makes us laugh. At first glance the stories just like a satire joke to corner sales peoples. Or if we look into the written moral of the story, the engineer want to say that he is much more intelligent than the sales peoples. Is it true that engineers are cleverer than sales peoples? Isn’t it just a show of arrogance of engineers? Or may be showing the frustration of an engineer that feels more intelligent but earning lower incomes compared to the peoples work in the financial world? Is it true that sales person imitating engineers’ methods? Isn’t it we, engineers, that should learn from the sales peoples? In the author opinion, an engineer, apart from good engineering skill, must also equipped himself/herself with financial knowledge and marketing skill in order to be able to sell his/her expertise in a valuable manner. In other words, the engineers must know what the sales peoples say: “You must know how to sell yourself!”

The deep excavation failures presented in this paper do not intend to blame any party or any system in the construction industry. It merely acts as examples to highlight to all parties involved in the construction industries NOT TO under-estimate the importance of geotechnical factors, and NOT TO over pressurize the pricing that lead to improper and dangerous cost cutting practices. In short: Do not treat the soils as step children, as the step children will take revenge with severe consequences!

Finally, with all the sincerity, the author apologizes for any inadequacy and any inconvenience caused by the write up in this paper.

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30 October 2011

To:        Ir. Tjie-Liong Gouw  
            Certified Geotechnical Consultant 

Subject:  Notification of Manuscript Acceptance

Dear Ir. Tjie-Liong Gouw,

We have received your final version of your camera ready paper entitled "Deep Excavation Failure Can They Be Prevented". Based on the review, your paper has been assigned to be orally presented as an invited lecture on the forthcoming International Symposium on Sustainable Geosynthetics and Green Technology for Climate Change SGCC2011 (Retirement Symposium for Prof. Dennes T. Bergado), which will be held from 7 to 8 December 2011 in Sofitel Grand Centara, Bangkok, Thailand.

Thank you very much and I am looking forward to seeing you soon.

Sincerely yours,

[Signature]

Prof. Dennes T. Bergado  
President, IGS-Thailand  
Secretary-General, SEAGS  
Director, ACSIG
DEEP EXCAVATION FAILURES, CAN THEY BE PREVENTED?

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ABSTRACT

The writer has been working in the field of geotechnical engineering since 1984, along the way he has seen a number of deep excavation failures, some with minor casualties, others involving a huge amount of economic loss, some cost no human life, others with a number of fatalities. This paper tries to discuss what could be the causes of those failures, from the possible technical to the non-technical reasons. It also tries to extract what can be learnt from those failures, starting from the lack of reliable soil investigation data, inadequate geotechnical design knowledge, poor execution, to poor quality control. The non technical reasons, such as: the lowest bidder win policy and its implication are also discussed. Finally, steps to minimize geotechnical failures are suggested.

Keywords: Deep excavation failure, software factor, quality control, lowest bidder win, prevention

INTRODUCTION

A few months ago, in a geotechnical mailing list, there is a simple but challenging question, i.e.: “Geotechnical failures – Do they happen and can we prevent them from happening?” It is a simple question to answer: “Do they happen?” the answer is very simple, that is: “There were many geotechnical failures, large or small scale, they are facts of life. However, a lot of the failures were unexposed to the outsider, the parties involved usually tried to settle the failures quietly among themselves.” However, to answer: “Can we prevent them from happening?” is a challenging task, as the answer is no longer simple. It needs in depth investigation on the causes of the failures, starting from the soil investigation report, design documentation, execution and supervision of the project, to the non-technical matter that usually initiated from too lower pricing of the project.

DEEP EXCAVATION FAILURES CASES

Inadequate stability analysis of an open cut excavation, often executed for basement constructions, can lead to a slope failure which in turn causing driven piles that had been put into place were subjected to large lateral force that lead to the failure of the piles (Fig. 1). The consequence of such a failure in a building foundation, new piles have to be reconstructed.

Insufficient toe penetration of steel sheet piles, would lead to excessive movement of the sheet piles toe, which often lead to kick in failure. This kick in failure would then lead to large and often sudden sagging of the ground behind the wall (Fig. 2). If this event were to take place near adjacent buildings and utilities, the buildings and utilities would have had collapse.

The earth pressure induced by soft clay was often wrongly calculated, as a result, a cantilever sheet piles wall systems was in total failure (Fig.3a) causing the adjacent road to collapse and traffics were severely interrupted. Further lateral movement of the soft soils was tried to be stopped by installing 60cm diameter soldier pipe piles (Fig.3b). The pipes were also casted with concrete, but it was NOT successful. Figure 3c shows that the pipe piles were eventually slanted to almost 30 degrees. One must understood that once the soil movement exceeds their yield stresses, it will be very difficult to stop further movement.
Fig. 1 – Failure of Open Cut Excavation that Lead to Driven Pile Foundation Failures - North Jakarta - 2005

Fig. 2 – Kick in Failure of Sheet Pile – Surabaya - 2007
Fig. 3 – Failure of Sheet Pile Walls; Further Soil Movement was tried to be stopped by Soldier Pipe Piles but Failed – West Jakarta 1995

All the previous examples of failures were taken place at very soft to soft gray to black clay. However, failure of retaining walls can also occur at relatively strong, medium to stiff clays shown in Figure 4. With 16m depth excavation, since the soil layer from 9m below was cemented sand with SPT blow count as high as 60, the engineer decided to retain the upper 9m of soil by installing 40cm diameter soldier driven piles up to 9m depth with center to center distance of 1.25m. The system was proved inadequate. The upper 9 m of the soil collapsed (Fig.4a), the capping beam and the soldier piles moved excessively and broken (Figs.4b & 4c).

April 21, 2004 a serious incident of excavation failure took place in Singapore, a country with stringent construction rules (Fig.6)! The failure had caused the loss of four lives, the collapse of pedestrian bridge, and the total cut off of a major highway, namely Nicoll highway. The project was a cut and cover excavation for an underground MRT (Mass Rapid Transit). The excavation was 33-34m deep, protected with 44.3m depth diaphragm wall along its two sides. Steel beams spanning from one side of the wall to the other side were installed as strutting/shoring system.

**TECHNICAL ISSUES THAT CAN LEAD TO FAILURES**

Based on the failure cases investigated, the author summarized the possible technical issues that often forgotten or ignored or wrongly calculated, in the design stage and in the execution phases, starting from the simple equation of earth pressure theory to the implementation of sophisticated finite element software.
Fig. 4 – Failure of Small Diameter Soldier (Driven) Piles. The Capping Beam and The Soldier Piles Moved Excessively and Broken – South Jakarta – 2004.
Fig. 5 – Ignorance Open Cut Excavation Led to a Building Collapse - China – 2010
Cohesion Factor in the Earth Pressure Formula

In the calculation of the lateral earth pressures acting on a retaining wall system, the engineers generally know the following formulas:

\[ P_{a} = k_{a} \sigma_{v} - 2c' \sqrt{k_{a}} \]  \hspace{1cm} (1)

\[ P_{p} = k_{p} \sigma_{v} + 2c' \sqrt{k_{p}} \]  \hspace{1cm} (2)

where:  
- \( P_{a} \) = active earth pressure,
- \( P_{p} \) = passive earth pressure,
- \( k_{a} \) = active earth pressure coefficient,
- \( k_{p} \) = passive earth pressure coefficient,
- \( \sigma_{v} \) = effective overburden pressure, and
- \( c' \) = drained cohesion.

The \( c' \) value in the above formula reduces the active earth pressure, on the other hand it increases the passive earth pressure, hence, over estimating \( c' \) will lead to unsafe condition. One has to understand that in soft normally consolidated soils, \( c' \approx 0 \), and even if the triaxial test results show the existence of \( c' \), which is normally the case of unsaturated samples, it is suggested to take \( c' = 0 \).

In total stress analysis where the undrained cohesion \( c_{u} \) prevailed, the \( k_{a} \) and \( k_{p} \) values for soft clay is equal to one, because the undrained internal angle of friction, \( \phi_{u} = 0 \). Note that soil investigation reports often show \( \phi_{u} > 0 \), this happened because the samples tested were not in a fully saturated condition; the water content somehow had reduced during the preparation or the keeping of the soil samples, whereas in situ soft soils are generally in a fully saturated condition.

One another factor that need to be understood is: for deep excavation, the passive earth pressure calculated by Coulomb theory shall be overestimated. It is suggested to use the passive earth pressure coefficient derived by Caquot and Kerisel (see Gouw, 2009).
If prestressed ground anchors or prestressed strutting are used, the earth pressure coefficient $k$ shall moves back and forth within the values of $k_e$ and $k_p$.

**Water Pressures**

Fluctuation of ground water tables must be investigated. In an area where rain intensity is high, the difference within the rainy and dry season can be of several meters. When excavation is executed near a river or sea shore, the influence of high and low tides to the ground water table also need to be investigated. Failure in estimating the ground water tables shall lead to the wrong calculation of water pressures acting on the retaining walls, and it can contribute to excessive movement of the retaining wall. In an adverse condition may also cause failure.

Observation of ground water table through soil investigation boreholes only is inadequate. It can lead to wrong elevation of the ground water table. The proper measurement should be done by installing observation wells and piezometers, best installed in every significant layer of soils. The measurement should span over the rainy and dry season. By employing this method, the correct water table during the dry and rainy season can be identified. The existence of artesian water pressure, if any, can also be identified. The measurement issues of the ground water table is elaborated in detail by the author in the papers titled “Pumping Test and Its Interpretation for Dewatering Purposes” (Gouw, 1994); “Dewatering” (Gouw, 2010).

When excavation is conducted near sources of water, such as: river, lake, reservoir, etc., the possibility of water seepage into the excavation area must be explored.

**Seepage Force**

Seepage of ground water toward the excavated area is often forgotten in analyzing the stability of earth retaining structure. The mode of the seepage depends on whether water can pass through the retaining wall or not.

For open cut excavations and retaining wall systems where water can seep/flow through the wall, e.g. soldier piles, the stability of the excavation shall be seriously impaired if ground water is allowed to flow through the slopes or the walls. Therefore, it is very important to prevent the ground water to flow out from the slope of the open cut excavations or through the walls of the retaining wall system. For that it is advisable to install dewatering wells at the perimeter of the excavation area (Fig. 7).

For an excavation with impervious retaining walls, e.g. diaphragm walls or secants piles, where the toe of the walls is located in a permeable soil layer, then the walls will not act as a water cut-off system. This means, water can seep from outside the walls into the excavation area through the permeable soil layer below the walls’ toe as shown in Fig. 8. This ground water seepage creates seepage force which increases the effective overburden pressure in the active side of the walls, and on the other hand, reduces the effective stress in the passive side of the walls. This means the seepage force increases the lateral pressure to the walls and decreases the passive pressure. A large seepage force may significantly reduce the effective overburden pressure and subsequently will induce piping and boiling. This effect of seepage force is often forgotten by inexperienced design engineers and contractors.

If the retaining wall is embedded into an impermeable layer (Fig. 9), there will be unbalance water pressure within the active and passive sides. When the base of an excavation is impermeable, say by jet grouting a layer at the base of the excavation, the base of the excavation is then subjected to an uplifting force (Fig. 10). Therefore, to withstand this uplifting force, the thickness of the base has to be calculated. Ignorance in calculating this uplifting force can cause failure.

**Artesian Water Pressure**

The existence of artesian water pressure can greatly affect the stability of an excavation. The weight of the soil from the excavation level to the top of the aquifer layer and the friction of the soil-wall system should be able to withstand the artesian pressure (Fig. 11); otherwise the base of the excavation shall fail. This type of failure is known as bursting or boiling. In a smaller scale, the seepage of the artesian water reduces the passive resistance of the soil. Undetected artesian water pressure beneath an excavation may lead to unsafe excavation.

**Squeezing / Soil Flow**

When soldier piles system is used as retaining structures for soft soils, soil squeezing or soil flow through the gaps within the soldier piles may take place (Fig. 12). This phenomenon may affect the stability of the structures/facilities adjacent to the excavation area. Therefore, it should be noted that the gaps within the soldier piles must be close enough to ensure the formation of arching (arching effect) where the soft soils could not penetrate or squeeze out of the gaps.
Fig. 7 – Ground Water Seepage through Soldier Piles.
Fig. 8 – Groundwater Seepage Through Impervious Wall

Fig. 9 – Unbalance Water Pressure

Fig. 10 – Impermeable Layer at Base

Fig. 11 – Artesian Water Pressure
Heaving

For braced excavation system, it is quite common that the design engineer forget to take into account the heaving mode of failure. This mode of failure can take place due to the weight of the soil columns, of 0.7 excavation width, at the sides of the excavation pushing inward from the bottom of the excavated area. If the bearing capacity of the soil beneath the excavation area is unable to withstand the soil column weight, then heaving failure can take place (Fig. 13).

Geotechnical Software

The advance of computer technology, made personal computers no longer a luxury item, it even becomes a necessity. Every consultant, contractor, and even almost every household have computers. However, one of the negative side effect is many peoples relied too much on the computer software. It is quite common engineers believe that the output obtained from geotechnical software calculation is an accurate solution for their problems at hand, especially to those engineers with inadequate knowledge and lack of experience in designing geotechnical works. In order to save cost, the contractors and consultants who owned sophisticated geotechnical software, such as: PLAXIS, CRISP, SIGMA, FREW, WALLAP, MIDAS, etc., felt that with those advance software they no longer need to consult geotechnical expert or geotechnical specialist. Realizing it or not, they believe the engineers they sent to attend the geotechnical software short courses are capable enough to design a geotechnical structures. They forgot the adage in computer application, that is: Garbage In Garbage Out. What is the garbage then?

- Wrong Application of Soil Model: There are many soil models available for geotechnical analysis, e.g.: Mohr-Coulomb Model (elasto-plastic model), Soft Soil Model (soft soil, soft soil creep, and critical state soil models), Hardening Soil Model (hyperbolic soil model), etc. Each of the soil models have its own
weakness, strength and suitability to be applied to a particular problem. Choosing the wrong soil model may lead to wrong estimation on the performance of the geotechnical structure. Mohr Coulomb Model is the most common method adopted. It is a simplification of non-linear soil behavior into bilinear soil model. This model does neither include stress-dependency nor stress-path dependency of soil stiffness. Generally speaking, when the safety factor in the design is taken to be less than two, the output of this calculation type is less reliable. Hardening Soil Model (Hyperbolic Soil Model) incorporates the loading history of the soil and strain depended stiffness, however it does not taken into account the softening due to dilatancy. This model is good for excavation problem. Soft Soil Model is good for the application of the situations dominated by compression. It is not recommended for excavation problems.

- Wrong Adoption of Soil Parameters: Use of drained shear strength for undrained condition and vice-versa. Wrong adoption of shear strength parameters. Wrong determination of soil stiffness. Over estimation of those values can lead to dangerous situation.

- Wrong Modeling of Undrained Condition in Mohr Coulomb Soil Model. It has to be noted that in Finite Element Software (PLAXIS for examples), there are three methods to model the undrained behavior (see Fig. 14).

**Method A (analysis in terms of effective stresses):**
- type of material behaviour: undrained
- effective strength parameters $c_v$, $\phi$, $\psi$
- effective stiffness parameters $E_{0v}$, $v$

**Method B (analysis in terms of effective stresses):**
- type of material behaviour: undrained
- undrained strength parameters $c = c_u$, $\phi = 0$, $\psi = 0$
- effective stiffness parameters $E_{00}$, $v$

**Method C (analysis in terms of total stresses):**
- type of material behaviour: nonporous or drained
- total strength parameters $c = c_u$, $\phi = 0$, $\psi = 0$
- undrained stiffness parameters $E_{00}$, $v_u = 0.495$

Fig. 14 – Three Methods for Modeling Undrained Behavior in FEM

Employing method A for undrained analysis in Mohr Coulomb model leads to overestimation of undrained shear strength as shown in the stress path diagram on Fig. 15. The stress path of Mohr Coulomb model will be perpendicular to mean effective stress axis ($p'$ axis) until it touched the failure line at an undrained shear strength higher than the real value of $C_u$. This over-estimated $C_u$ can be prevented by adopting method B where the real $C_u$ value is used as input in the program. However, it has to be noted that, either Method A or Method B, both does not follow the stress path of undrained behavior of real soil that curves upward to the left.

**Construction, Supervision, and Monitoring**

The quality of the construction is one of the key factors in assuring the safety of a deep excavation. Good construction method, supervision and monitoring system must be adopted. The design assumption must be clearly stated in the design report and it has to be explained to the contractor. The contractor must pay attention to all the design assumptions, if there is any discrepancies in the field, the contractor must report and carry out coordination with the designer. For example: The embedment depth of retaining wall executed differs greater than the tolerance given by the designer. A shallower embedment depth may provide inadequate fixity. Larger embedment depths may signify the existence of softer layer than predicted by the designer. All this may affect and harm the stability of the retaining structure.

Geotechnical instrumentation must be installed to monitor the lateral movement of the retaining walls, to measure the settlement of the surrounding area, and to monitor the water level in the excavation area as well as outside the retaining walls. Compared the measurements with the predicted values obtained in the design stage. If the values exceed the tolerance given by the designer, the contractor must alert the designer and all the parties involved to carry out the necessary review and action.

**NON TECHNICAL FACTORS**

All the parties involved in the construction industries definitely know the bidding system where
the words "lowest bidder wins" are well known. The intention of this type of bidding system is to achieve cost efficiency. However, it also carries the negative side effect, that is: the tender participants will try to cut cost here and there, very often, by sacrificing quality and safety. The participants that lost in one tender would bid lower in the next tender, then the ones lost in this tender will also bid lower in subsequent tenders, and the trend goes on until it reaches an unhealthy state where the consultants, contractors, and sub-contractors do not have enough profit margin. The effects of this behavior are lengthy, among others are:

- Consultants cannot pay qualified engineer in a reasonable manner, they do not have enough budget to enhance the knowledge of their engineers; very often they even do not have money to upgrade themselves. Unable to attend good seminar and courses, unable to buy licensed software, not to say to develop research and development department. Low and inadequate income make good engineers seek for other professions. The effect? Of course the soil investigation report and the design quality will be lower and lower. Figure 16 shows low pricing lead to wrong soil investigation report due to lack of proper quality control.

![Grain Size Distribution Curve](image1)

![Mohr Chart CU Test](image2)

Fig. 16 – Wrong Soil Investigation Report due to Bad Pricing

- The main contractors shall press sub-contractor pricing, then who will the sub-contractor press? The clear facts are everyone will cut cost here and there. The first stage is trying to cut construction temporary supporting elements (temporary work), for example: omit the capping beam that tie diaphragm walls panels / soldier piles into one system, omit some waller beams in a strutting or ground anchoring system, reducing the number of struts, cut cost on the dewatering system. When cost cutting is successful in one project, the contractors are getting daring from one project to another. They forgot that the soil condition varies from one place to another. This kind of cost cutting on temporary work which is often take place in the execution of deep excavation, can lead to fatal failure.

One of the causes of the failure on the cut and cover MRT excavation shown in Fig. 6 was the improper strutting system. Figure 17 shows the buckling of the waller stiffer. It can also be seen that the waller was not a continuous beam, therefore, when one segment of the diaphragm wall was subjected to higher force than predicted, the redistribution of load to the adjacent diaphragm wall panels could not take place. Another indirect factor that contributes to the failure was the contract value was too low; the contractor price was way too low compared to its nearest competitor.

Other examples of cost cutting on temporary work supports that lead to failure of mat foundation reinforcement fabrication occurred in Singapore on May 2004. At that time the stacks of six layers 32 mm upper reinforcement of the mat foundation collapsed, hitting and causing the loss of life of the workers working underneath the reinforcement (Fig. 18). The collapse of the reinforcement must be due to inadequate vertical supports, and that was due to cost cutting effect. It was a bitter lesson, too much cost cutting lead to fatal failures!

- The next effect of unreasonably low cost is the consultants / contractors try to cut overhead. They do not have budget to hire qualified engineers, especially good geotechnical engineers. The consequence is they are unable to see the danger that may take place. Despite the fact that the engineers very often have to work overtime with no compensation at all, the salaries of the engineers are inadequate. While the cost of living increases year by year, the engineers' salary hardly moves up, sometime they even get reduced salary under the reason of economic crisis. Compared to their peers in the financial world their salary are way too low, therefore, the capable engineers start to seek for another professions that give much better compensation. Of course the scarcity of good and qualified engineers leads to lower quality of construction work. The author had written the exodus of construction engineers to other field
of professions in a paper titled "Engineers and Their Problems" (GOUW, 2003).

- The saddest thing of all is the engineers that pressure engineers, just merely to follow the instruction of the owners. The engineers that act as a quantity surveyor (QS) often carry out the "price negotiation" with very shallow basis. They collected lowest pricing of every items from every contractors, for example: A was lower in boring, they took boring price from A; B was lower in concreting work, they took concreting price from B; C was lower in reinforcement price, they took reinforcement price from C; and so on. The QS often does not (and does not want to) understand geotechnical
work. They often use the sentences: “Contractor A can do it with this price, why can’t you do it?” They could not see the potential problems of low costs and they do not want to understand what they are negotiating at. Their attitude shows that they are not qualified to be named QS. Ones do not need an engineer for doing that way of negotiation! A senior high school graduate is enough for carrying out that “wet market” like negotiation! Good QS must understand what he is negotiating at, how to carry out the construction work, want to understand and want to seek and to survey for proper pricing of every item he is negotiating at. He must give feedbacks to the owner on the proper price level, and not only pressuring the pricing of the consultants/contractors/subcontractors.

8. Whenever necessary, carry out quality control testing, for examples: carry out PIT or Sonic Logging test to check the soundness of piles; performed static loading test or PDA test to check the capacity of piles; etc.

9. In handling a new type of problem which is complex and difficult, it is better to seek an advice from fellow capable engineers.

10. Be honest to our own capability and never pretend to be clever on everything. Even in the field of geotechnical engineering, a geotechnical expert will not master every aspect of geotechnical engineering and geotechnical construction.

If the above guidelines are followed, then the author believes that risk of geotechnical failures can be minimalized.

CLOSURES

The author ever received an email telling a story about ENGINEER vs SALES PEOPLE. The story written by a master degree geotechnical engineer can be a brain stimulating idea for us to learn more about finance and marketing in order to sell our engineering product and expertise to the economist (owner) with reasonable prices. The story goes like this:

The First...

Eleven people were dangling below a helicopter on a rope. There were ten sales people and one engineer. Since the rope was not strong enough to hold them all, they decided that one of them had to let go to save all the others. They could not decide who should be the volunteer. Finally the engineer said he would let go of the rope since engineers are used to do everything for the company. They forsake their family, don’t claim all of their expenses and do a lot of overtime without getting anything in return. When he finished his moving speech all the sales people began to clap...

Moral:
Never underestimate the powers of the engineer.

The second...

A group of engineers and a group of sales people take a train to a conference. Each sales person holds a ticket. But the entire group of engineers has bought only a single ticket. The sales people are just shaking their heads and are secretly pleased that the arrogant engineers will finally get what they deserve.
Suddenly one of the engineers calls out: "The conductor is coming!". At once, all the engineers jump up and squeeze into one of the toilets. The conductor checks the tickets of the sales people. When he notices that the toilet is occupied he knocks on the door and says: "Ticket, please!" One of the engineers slides the ticket under the doors and the conductor continues merrily on his round.

For the return trip the sales people decide to use the same trick. They buy only one ticket for the entire group but they are baffled as they realize that the engineers didn't buy any tickets at all. After a while one of the engineers announces again: "The conductor is coming!" Immediately all the sales people race to a toilet and lock themselves in.

All the engineers leisurely walk to the other toilet. Before the last engineer enters the toilet he knocks on the toilet occupied by the sales people and says: "Ticket, please!"

And the moral of the story?
Sales people like to use the methods of the engineers, but they don't really understand them.

The third ...
Once upon a time three sales people were walking through the woods and suddenly they were standing in front of a huge, wild river. But they desperately had to get to the other side. But how, with such a raging torrent? The first sales guy knelt down and prayed to the Lord: "Lord, please give me the strength to cross this river!"

The Lord gave him long arms and strong legs. Now he could swim across the river. It took him about two hours and he almost drowned several times. But: he was successful!

The second sales guy, who observed this, prayed to the Lord and said: "Lord, please give me the strength and the necessary tools to cross this river!"

The Lord gave him a tub and he managed to cross the river despite the fact that the tub almost capsized a couple of times.

The third sales man who observed all this kneeled down and prayed: "Lord, please give me the strength, the means and the intelligence to cross this river!"

The Lord converted the sales man into an engineer. He took a quick glance on the map, walked a few meters upstream and crossed the bridge.

Send this to an intelligent engineer so that they have something to smile about; and to the sales people if you think they can stomach the truth!

The above story makes us laugh. At first glance the stories just like a satire joke to corner sales peoples. Or if we look into the written moral of the story, the engineer want to say that he is much more intelligent than the sales peoples. Is it true that engineers are cleverer than sales peoples? Isn't it just a show of arrogance of engineers? Or may be showing the frustration of an engineer that feels more intelligent but earning lower incomes compared to the peoples work in the financial world? Is it true that sales person imitating engineers' methods? Isn't it we, engineers, that should learn from the sales peoples? In the author opinion, an engineer, apart from good engineering skill, must also equipped himself/herself with financial knowledge and marketing skill in order to be able to sell his/her expertise in a valuable manner. In other words, the engineers must know what the sales peoples say: "You must know how to sell yourself!"

The deep excavation failures presented in this paper do not intend to blame any party or any system in the construction industry. It merely acts as examples to highlight to all parties involved in the construction industries NOT TO under-estimate the importance of geotechnical factors, and NOT TO over pressurize the pricing that lead to improper and dangerous cost cutting practices. In short: Do not treat the soils as step children, as the step children will take revenge with severe consequences!

Finally, with all the sincerity, the author apologizes for any inadequacy and any inconvenience caused by the write up in this paper.

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