A REVIEW OF GROUND TREATMENT OPTIONS, ISSUES AND CONCERNS FOR DEEP EXCAVATIONS IN SINGAPORES' KALLANG FORMATION

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ABSTRACT: The challenges faced in undertaking deep excavations in the Kallang Formation are well known, in particular those relating to controlling ground movements. The most common solution has been the introduction of Jet Grout Piles (JGP) to form stiffer slabs of treated ground within and below the excavations. These slabs have proved successful in controlling movements. They can however introduce new problems such as heave and lateral movements during installation and despite tighter controls over installation procedures the doubt occasionally remains over their lateral continuity. More recently different solutions are being sort to controlling ground movements, this change has been driven by the need to control ground movements even further, combined with economic and program issues. This trend of alternative ground treatment solutions can be seen in current construction projects and their various merits are reviewed. Despite this JGP is still a viable option; however it needs to be considered and understood from the design stage through to its implementation where tight construction control needs to be employed to maximize its benefit.

Keywords: Ground treatment, construction control, deep excavations, ground movement, another.

INTRODUCTION

Major underground work in Singapore commenced in 1983 with the start of the MRT network and over the last 25 years has continued, almost exponentially. The existing MRT network alone contributes 64 stations and 110 km of rail tunnels. The current focus of work is in the busy and congested Marina bay area, with the commercial developments of the Integrated Resort (IR), Marina Bay Financial Centre (MBFC) and the latest phase of the MRT, Downtown line 1 (DTL1) (figure 1). One of the major engineering challenges to this work is the same as that faced 25 years ago, controlling the stability and movements of these excavations in the very soft deposits of the Kallang Formation, in particular the Marine Clay, which can extend to 55m below ground level.

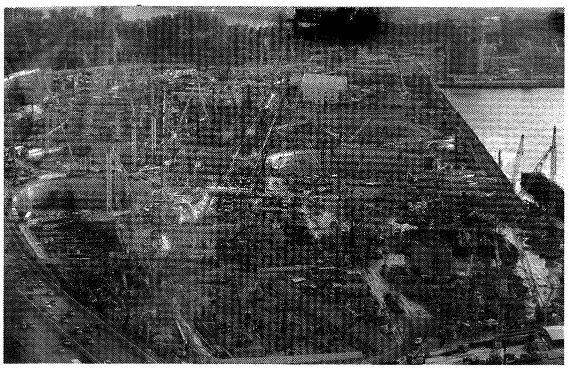


Fig. 1 Construction works at Marina Bay: IR, MBFC and DTL1

A frequently used approach is to install stiff JGP slabs of varying thickness within the excavation to increase stability. Over time techniques have evolved through single to triple tube and become more sophisticated, but the basic premise has remained the same. Although this solves problems in the design stage it introduces a new range of complications during construction.

[1] Land Transport Authority, Singapore

Too frequently the designer indicates a block of JGP on a drawing, assumes an improved strength and stiffness in the design, without considering the implications during construction. With todays' increasingly tight construction programs combined with heightend awareness of the need to control ground movements a range of new problems are created by the JGP. These need to be considered and evaluated during design and the potential for alternative solutions also considered.

In recent years JGP has been seen as the first ground treatment solution to controlling the Kallang Formation, there are others, and depending on the circumstances, they can frequently be more appropriate. Recently jet mechanical mixing (JMM), deep cement mixing (DCM) and cross walls have all been used successfully to control the Kallang Formation.

The decision to use these techniques was based on more than just design alone. Consequently for future design these contributory factors must be assessed in the decision making process during the selection of ground treatment. Currently in Singapore ground movements are required to be limited 0.5% H, H being excavation formation depth, further highlighting the role of ground treatment to the success of a deep excavation. This importance is additionally reinforced by the tighter construction programs, on projects necessitating ground treatment to be installed as rapidly and efficiently as possible. Therefore the choice of the most appropriate ground treatment for a project plays an important role in the success of the project.

GEOTECHNICAL PROPERTIES AND CHALLENGES OF THE KALLANG FORMATION

The Kallang Formation is dominated by the marine clay which is generally a near normally consolidated clay deposited in two phases, known as the upper and lower marine clay. The formation also includes soft organic clays, loose fluvial sands and moderately stiff fluvial clay, generally found between the upper and lower marine clay or above it. They compromise approximately 15% of the formation and have great lateral variability.

Despite making up a small proportion of the formation they should not be discounted as frequently they present problems during the construction phase of projects.

The marine clay has a Plasticity Index ranging from 40% - 60% and a low undrained strength that increases with depth, but not significantly, (figure 2). This figure illustrates five different design lines used for excavations in Singapore, with a strength range of about 30kPa at any given depth. This variation in strength is very dependant on the marine clays depositional history and in particular its recent history. The marine clay at Boon Keng is located 3km inshore and is a normally consolidation clay, consequently has the best strength profile. Moving towards the sea and the recently reclaimed areas of marina bay the strength profile drops, with a marked difference in the most recently reclaimed land, that area currently under development. Here the marine clay is undergoing consolidation from the recently placed fill and further evidence of its under consolidation can be seen by the positive pore water pressures that exist, in excess of 5m recorded in this location. It is interesting to note that there is considerable inconsistency in the positive pore pressures and the level of under consolidation of the clay in the marina bay area. The reason for this variability is primarily linked to the presence of fluvial sands, which in some locations, allow preferential drainage paths making the consolidation process more rapid.

It is this low strength that presents major challenges during excavation, in terms of basal stability and lateral deflections. Depending upon the exact nature of the marine clay the critical stability number of 6 is reached somewhere between 6m to 8m below ground level. At this point the clay can begin to squeeze through any gaps in the retaining system, cause problems from a basal stability standpoint and if the excavation is much deeper pose significant problems in terms of lateral movements. During the construction of the 18m deep Bugis station for the EW line, utilizing 1.2m thick diaphragm walls and 7 temporary strut levels, a maximum wall deflection of 150mm was recorded (Hulme et al 1990).

In another example of a more extreme and recent case, observed wall deflections reached in excess of 700mm in a deep excavation in marine clay with a diaphragm wall of 800mm, construction was completed successfully, but not without major associated problems.

Movements of the above magnitudes are no longer acceptable given the urbanization of Singapore. Movements need to be controlled to ensure that adjacent structures are not impacted by the excavation. To ensure that structures are not unduly distressed current practice is to limit movements to 0.5% H, or less if settlement sensitive structures are adjacent. Purely from a structure protection perspective this approach works well, however it is suggested that there is little merit in applying it to the greenfield.

Engineering theory and observations of these movements demonstrate that the zone of maximum movement occurs below the current level of excavation, therefore any mitigation measures need to be implemented prior to excavation. Although struts can be used to reduce movements there is a limitation to their effectiveness. They cannot control the movements that occur ahead of the excavation face and closer spacing leads to diminishing returns in reducing movement, higher costs, and a more difficult working environment due to crowding and consequently extending programs. Increasing the stiffness of the retaining system can help reduce movements but not enough, and diminishing returns again are faced as diaphragm wall thickness increases, to the point where they becomes uneconomic. The introduction of improved ground ahead of the excavation can substantially reduce movements; JGP was first carried out in Singapore for the construction of Newton Station on phase 1 of the MRT and has subsequently been used on over sixty deep excavations. The process involves a high pressure jet to precut the soil, and then the delivery of cement grout to mix with and partial replace the soil, the balance of the soil being expelled to the surface.

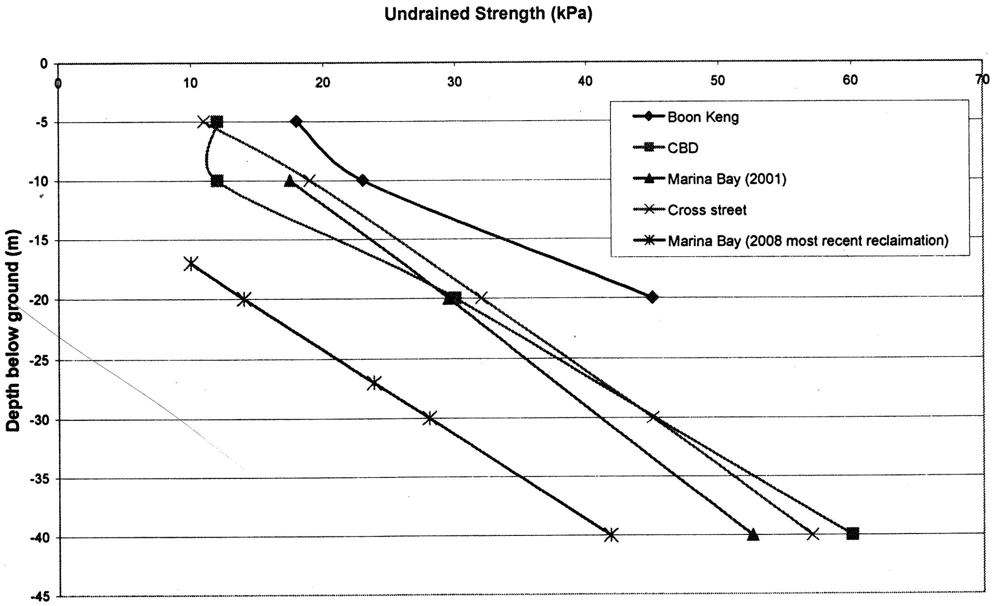


Fig. 2 Range of undrained strength vs depth used for various designs in Singapore

DESIGN CONSIDERATIONS

In design generally JGP is shown as a specific thickness on a design drawing with a strength and stiffness attributed to it, these parameters being derived from common practice and the modeling of the excavation. Although a relatively simple concept, the design benefits of the treatment should be fully explored at the design phase to optimize its position and its' potential strength taking into consideration, both previous precedent and workmanship.

Design Benefits of Ground Treatment

The numerical benefits of JGP can only be demonstrated in theory, a single relatively thin slab beneath an excavation can be shown to reduce movements and bending moments by approximately a third (Osborne et al 2005), figure 3. Obviously different configurations and arrangements can result in different savings. Generally the most effective use of a slab is directly beneath the base slab of the excavation, but depending upon the exact depth of excavation and depth of soft clay, more than one slab may be required. There can be benefit in the use of a sacrificial slab within the excavation, however its position must be directly below a structural member such that that member replaces the slab before it is excavated out. If not the sacrificial JGP can cause more problems than solutions as it is excavated throwing large loads very rapidly into the struts above.

Design Strength and Stiffness

This improvement is usually achieved using a design strength, (Cu) in the range of 300-350 kPa, an equivalent UCS (qu) of 600-700 kPa and a stiffness (E) of 150 MPa. The achievable strength is related to the cement content used, with a typical relationship of 1.1:1 water: cement used. Testing is carried out at 28 days to validate design parameters, however Kamruzzaman et al (2005) have demonstrated that JGP strength gains continue for a year, as chemical pozzolanic reactions continue, further doubling the strength from that achieved at 28 days.

If time within the construction program permits the option of utilizing these additional strength gains should be explored.

In situ testing of treated ground shows that these parameters are considerably lower than that actually achieved in the ground, (figure 4), when good quality control is practiced during excavation. The average UCS achieved across three sites on DTL1 varied form 2847 kPa, 2470 kPa and 1748 kPa, generally six times greater than that required, together with some upper bound values in excess of 8000 kPa. These strengths compare well with those measured for earlier phases of the MRT. However looking purely at the strengths achieved does not always reveal the full picture. For site C although good strength results were achieved 55% of the core samples taken were too poor to test and contained little or no JGP, resulting in a major regrouting exercise. This being the reason, therefore, for the lower design strengths used, on top of a further reduction by FoS during design, to account for any inconsistency within the JGP slab.

From a stiffness perspective JGP demonstrates brittle failure during unconfined compression testing, with strain at failure in the range of 0.5 – 1.5%, this behavior is governed by the cement content, less cement the more ductile the failure. This relationship needs to be understood and considered during both design and construction as such failure is more prone to result in sudden and dramatic load shifts and catastrophic failure. The relationship between strength and modulus has been quoted as E/qu =200 or E/Cu = 400, Wen (2005) and more recently at a lower value, E/qu = 100 or E/Cu = 200 Wong et al (2006). These figures were based on the results from NELP C908 and CCLP C824 test results, respectively. More recent test result from 3 contracts on DTL1P support the relationship of E/qu = 200, although there is some notable scatter, (figure 5).

As the achieved strengths show, if the continuity of the slab can be guaranteed as on all but one project, higher parameters could have potentially be used in the design with confidence, leading to a more economical design. With the advent of automated logging of JGP installation providing a quality management path for control and a greater understanding of the processes involved in forming the JGP columns, much greater control over installation should be achievable. The potential to use higher design parameters should be explored further, what remains is to address workmanship during installation to guarantee continuous slabs.

CONSTRUCTION ISSUES IN GENERATING A CONTINUOUS SLAB

The implications of not achieving a continuous slab of treated ground are immense. In the worst case it can result in failure of the slab leading to a collapse of the excavation (Lim & Tan 2003) or can contribute to a collapse as in the infamous case of Nicoll Highway. Alternatively it can result in greater than predicted movements threatening the integrity of the retaining system and having major impact on surrounding structures. As a result, in Singapore, installation procedures and testing frequency have been enhanced to ensure such occurrences do not happen again. This does not solve the problem but aids in identifying any inadequacies within the JGP slabs. These then need to be rectified with considerable time and cost detriment to any construction project. In the authors' current experience when testing of installed slabs demonstrates deficiency within the slab these deficiencies are always linked with poor installation procedures.

There are several reasons, some simple, most more complex, as to why gaps in treatment occur. One of the most obvious lies in a pile or piles being omitted during installation. This can occur on a busy construction site with many different activities occurring simultaneously. Therefore following strong quality control procedures and a suitable numbering system is essential to ensuring the designed JGP arrangement is completely installed. As part of the quality control all the jet grout parameters should be data logged automatically to ensure that designed parameters are followed and to allow verification at a later date. The more complex issues relate to the jetting for the installation.

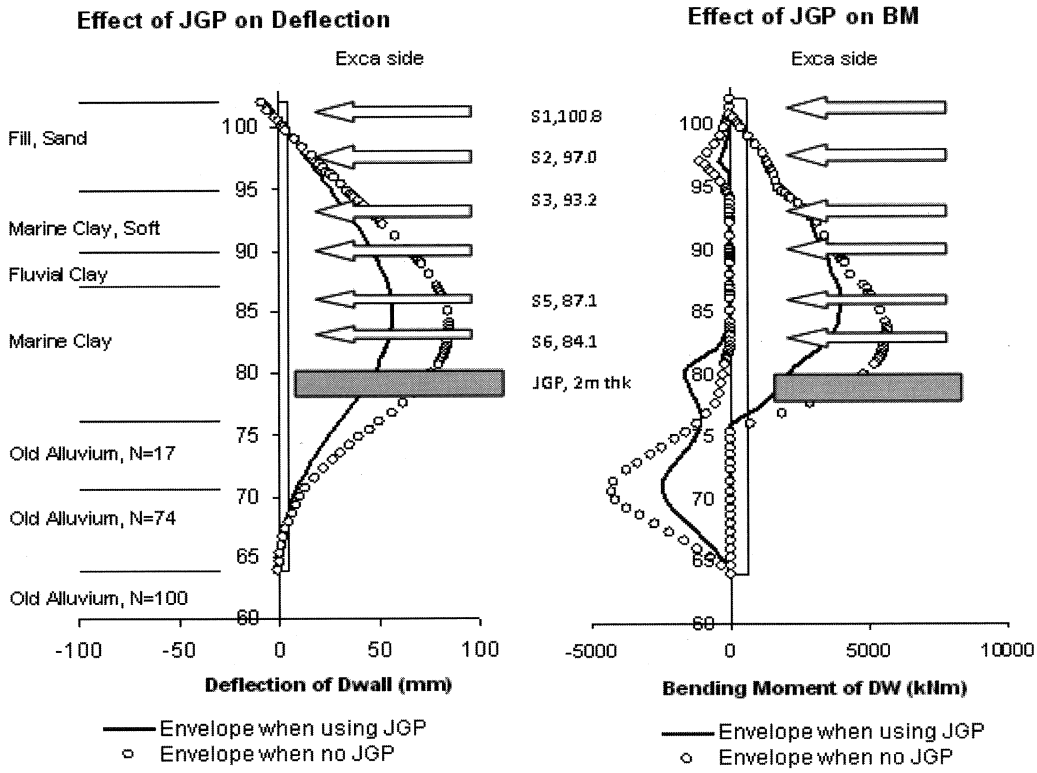


Fig. 3 Benefits of a single JGP slab

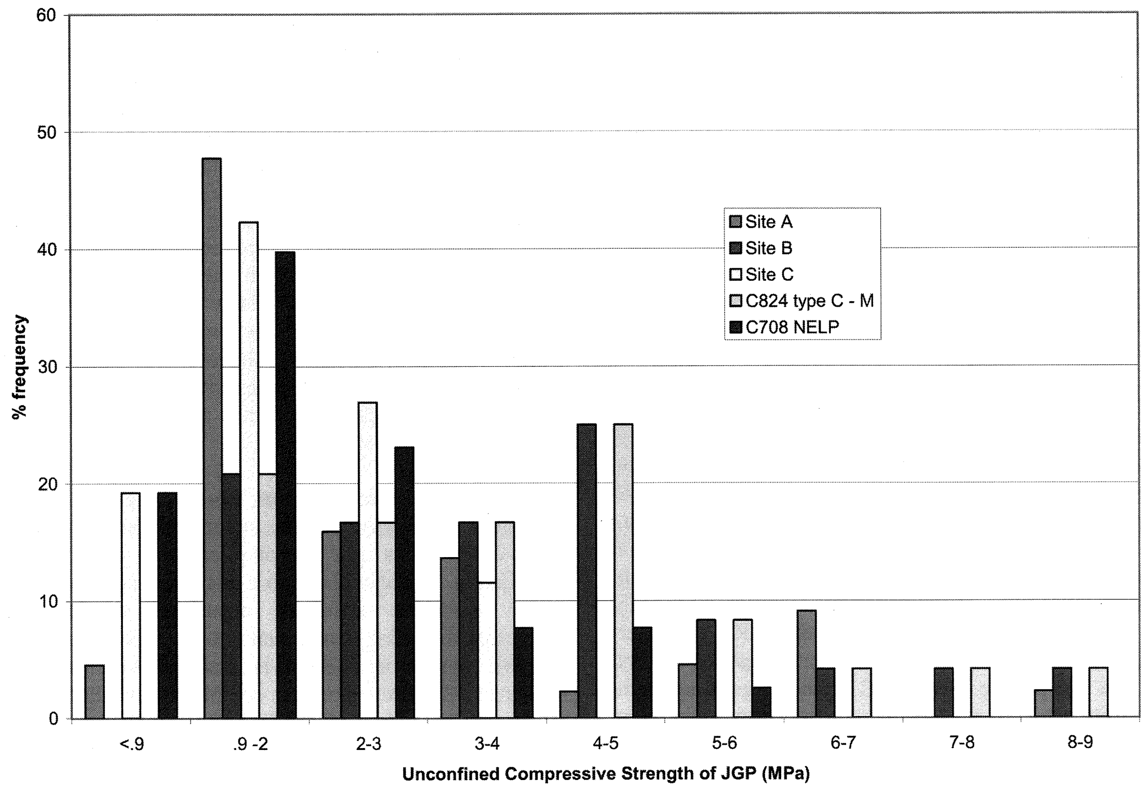


Fig. 4 Range of achieved Grout strengths

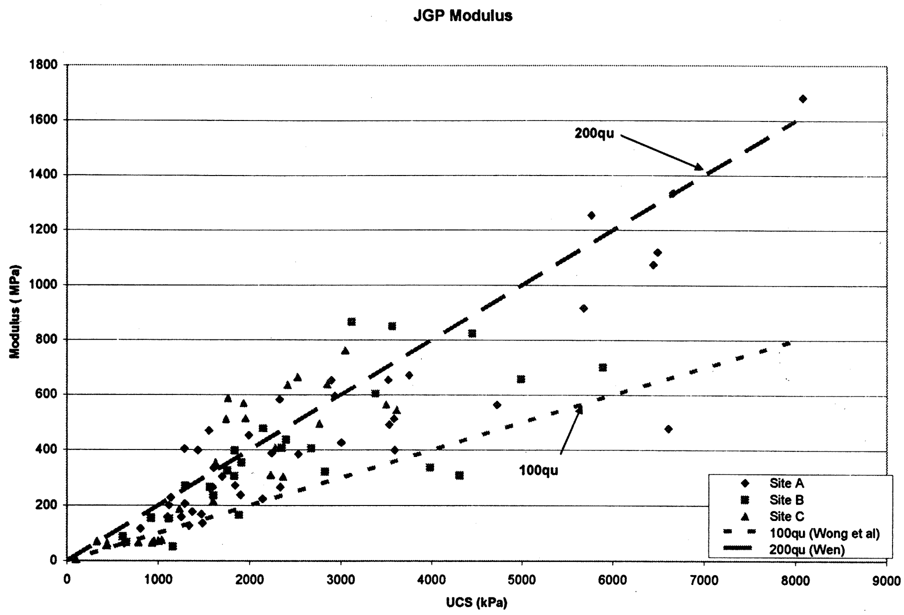


Fig. 5 Relationship between Modulus and UCS

Table 1 Grouting Parameters used on NELP & DTL1P

Operating parameters	NELP (Wen)	DTSS (O'Carrol et al.)	DTL1P – Site A	DTL1P – Site B	DTl1P – Site C
Diameter (m)	Various	1.6	2.2	2.2	2
Water pressure Pw (MPa)	35 – 45	40	25 – 30	25-30	-
Air pressure (MPa)	0.7 – 1.5	-	0.7 – 1.0	0.7 - 1.0	1
Grout pressure Pg (MPa)	7 – 11	13-15	40 +/- 2	40 +/- 2	40
Water flow rate Qw (l/min)	75 -750	130-150	-	-	-
Grout Flow rate Qg (l/min)	62 – 105	100 – 120	240 +/- 10	240+/- 10	180
Withdrawal speed Vt (min/m)	8 – 10	10-12	10	10	10.7
Rotation speed (rev/min)	5 - 10	5-10	9-10	9-10	4-7
Min UCS qu (kPa)	Various	600	700	600	600
Youngs Modulus E (MPa)	Various	150	150	150	150

Jet Grout Energy

The choice of design diameter is crucial to achieving a full and complete JGP slab. The most common failing during testing is an absence of grout at the extremity of the column resulting in an untreated zone of marine clay. An achievable diameter is a function of the ground condition and the grouting parameters used, notably water and grout pressures and volumes and the withdrawal speed. These parameters have evolved over time, but at any given period tend to be standard across varying grouting contractors. Table 1 illustrates a number of different design diameters used previously in Singapore and the parameters used to achieve them. There will be variation depending upon site conditions therefore any grouting design should be verified by an onsite trial. It is interesting to note that the major changes since NELP and DTSS are in using a lower water pressure for precutting, but a higher grouting flow rate during injection to achieve a slightly larger column diameter.

The importance of the correct jetting parameters in achieving a complete pile of jet grout was demonstrated by J O'Carroll et al 2003. They introduced a calculation that defined jetting parameters in terms of jet grout energy.

$$E_j = P_w Q_w + P_g Q_g / V_t \quad \text{(MJ/m)} \qquad (1)$$

where,

P_w and P_g = water and grout pressures in MPa, Q_w

and

Q_g = water and grout flow rates in m^3/h, and

V_t = withdrawal speed (m/h).

They demonstrated the importance of jet grout energy input to the creation of a complete JGP column. Using a minimum energy of 75MJ/m a 1.6m diameter pile could be created in marine clay at a depth of 25m bgl. From comparison of core recovery against energy input it was shown that when the energy input dropped below 75MJ/m the quality and RQD of the recovered core was reduced. It is noted that not all these parameters are always listed and strongly suggest that they should be. Although a useful indicator of what diameters and strengths can be achieved, as well as reinforcing the importance of the five parameters involved in the creation of a pile there is a further factor to be considered during the actual grouting installation, that of pressure relief or cavity expansion

Cavity expansion

During installation of JGP columns by far the biggest problem is caused by cavity expansion within the ground. The mechanism for this is very frequently perceived as being the high pressures used to deliver the grout into the ground, this is never the case and is major misconception. Although the grouting pressure may appear high at 40 MPa, as the grout is expelled through a nozzle with a typical diameter of 1.4mm its pressure is significant diminished, equating to a pressure of less than 0.07 kPa over a 1m^2 area of wall.

The driving mechanism for cavity expansion, which causes uncontrolled heave and lateral movements, is the inability to adequately balance the input and output of materials, resulting in a buildup of pressure in the ground. For this to occur the pressure generated within the JGP cavity must exceed the resisting force, the total vertical stress combined with the strength of the material being grouted, (figure 6). Once this occurs, pressure builds up very rapidly causing expansion and then fracturing of the ground and the JGP's influence can be considerable, as much as 30m. This phenomenon has been observed on site with JGP slurry seen bubbling in a diaphragm wall trench under excavation at a distance of 30m from the point of JGP injection.

The control of cavity expansion is currently an issue on a number of construction sites with some jet grouting contractors seemingly unable to adequate control these movements. Shirlaw et al. (2003) discusses this issue in detail and names a number of projects where cavity expansion has been successfully controlled in the past. The fact that cavity expansion can be controlled is further demonstrated on DTL1P with site A being very successful, installing a 4m slab adjacent to sensitive structures, diaphragm walls and an MRT without any recorded heave or lateral deflection. For JGP to be truly effective a delicate and equal balance between cement added and sludge expelled during the installation of the jet grout column must be maintained. The most critical case occurs if insufficient material is expelled. This makes achieving the design diameter more unlikely as energy is wasted in attempting to force material out and not utilized for cutting. A secondary, but major consequence in the urban context, is the creation of lateral and vertical movements, which have significant detrimental negative impacts. As detailed in Shirlaw et al (2003) to prevent cavity expansion four major factors must be considered:

- The density of the sludge
- The rate of injection which influences the volume of material to be removed
- The angle of the hole, greater the angle the greater the resistance
- The size of the clear annulus between the jet grout monitor and the outside of the hole.

Of the four criteria the annulus size is the most critical and the most overlooked. It is recommended that a hole with a minimum diameter 300mm is used and kept permanently open by a casing, which is installed over the centre of the column to be formed. The bottom of the casing should be within 3.5m, preferably closer, to the point of injection to enable sludge to enter the casing and have a free passage to the surface.

Close supervision should be carried during grouting and if sludge return is not apparent, grouting should be temporarily terminated and cutting with water resumed to clear any blockage.Following this approach, is the only proven technique to control cavity expansion during JGP. The use of relief casing, even up to 1m diameter, separate from the grouted hole does not work, as by the time the relief casing is utilized cavity expansion has taken place and movements are occurring. Where cavity expansion is not controlled, testing by core samples frequently demonstrates that the full diameter has not been achieved.

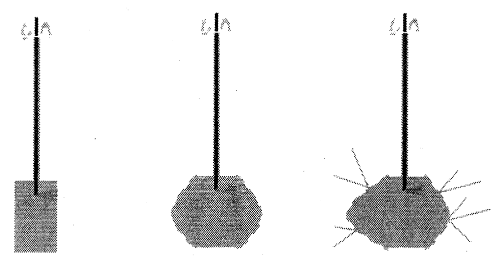


Fig. 6 Stages of Cavity expansion

Heave within the urban environment is not acceptable as it can damage buildings, utilities and roads, the most notable example of this being 550mm of heave caused by JGP under Robinson Road for phase 1 of the MRT (Berry et al.), which resulted in over a million dollars (S) of utility damage (Hulme et al 1990). There is also the lateral impact to be considered. The grouting is carried out against the retaining system and any lateral pressure will have a detrimental effect on the system. For a sheet pile wall this could cause declutching of the sheet piles, leading to potential 'squeezing' failure during excavation. In the case of a diaphragm wall, although a stiff system, deflections of 45mm on a 0.8m thick wall and 35mm on wall thickness in the range of 0.8 - 1.2m have been recorded, on C706 of the NELP and the construction of the Singapore Post Centre respectively. More recently there have been unconfirmed reports that wall deflections of 100mm have been caused by JGP. These movements cause problems, particularly where the walls are designed as part of the permanent works. They result in locked in moments that are opposite in direction to the major moments designed for, and may exceed bending moment capacity on the outer face. In addition these movements have the potential to cause waterproofing problems as they will certainly not impact the wall in a uniform manner, and can open potential water paths through the wall.

Variable Ground Conditions

A further complication in achieving the required design diameter of JGP columns lies with the ground itself. The fluvial clays (F2) and sands (F1) within the marine clay are variable and stiffer, with a SPT N range of 8-30 and 3-30 respectively.

Consequently to form the same size columns as for the marine clay either requires different JGP parameters or closer spacing of columns to enable full coverage. This is frequently not considered at the design stage due to the variable presence and thickness of the F1 and F2, which must be identified as far feasibly possibly by the designer. If not this then becomes a construction problem, needing alternative solutions on site to resolve and therefore a program risk. Such risk should ideally be engineered out at the design phase.

ALTERNATIVE SOLUTIONS

Although JGP previously has been the preferred solution to solving issues related to ground movement during deep excavation in marine clay, alternative solutions are gaining popularity. This is due to the combination of the unreliability in achieving a consistent JGP slab and problems caused by ground movement during installation, as grouting contractors do not always follow appropriate control measures. The current preference for these alternative solutions lies in the fact they reduce the construction risk. As these different solutions are explored other benefits are becoming apparent.

Cross Walls

Currently the most prevalent alternative is cross walls, a technique that is being widely used on DTL1 and on occasion replacing JGP as a more viable option during construction. They are a robust and flexible option, designed to span across the excavation, one panel per wall, providing a stiff restraint in between untreated zones. They can be used purely above or below the base slab or a combination of both, with a construction preference for below the base slab. They are generally unreinforced or lightly reinforced and with thicknesses and depths easily varied to suit ground conditions and design requirements. This trend is not exclusive to Singapore but can be seen elsewhere, with cross walls being used adjacent to some very sensitive structures for the Rome metro in Italy.

From a time perspective they frequently are a better option as they can be installed rapidly, considerable quicker than a comparative area of JGP and commonly by the same plant that is installing the retaining system. This maximizes the usage of the available plant and reduces the number of interfacing sub contractors on site. Preliminary indications are, that from a cost perspective cross wall are a significantly more economical option. In terms of controlling ground movements they are more effective than JGP both in theory and in practice. For computer modeling predictions for excavations, cross walls can obviously use a considerably higher strength and stiffness than JGP and this inhibits bending moments movement, if the influence of the cross walls is smeared across its diaphragm wall its influence can be further enhanced. Although a direct comparison is difficult as the geometry of cross walls and JGP slabs always varies preliminary studies show, that in theory, cross walls are more effective. The key issue in controlling the movements is in the interface between the cross wall and diaphragm wall, this needs to be as clean as possible to allow for direct transfer of load without movement, and not have a significant amount of compressible material at this contact that allows the diaphragm wall to move on to the cross wall.

In terms of actual performance on site there is little available data to date, however results from Pasir Panjang station excavation of the Circle line Chua et al. (2008) demonstrate the effectiveness of cross walls keeping diaphragm wall movements to the order of 8mm on a 20m deep excavation in Jurong Formation, in comparison with the design prediction of 13.5mm. Early indications of the performance of the cross walls on DTL1 support this, with preliminary observed movements being notably less than design predictions.This is illustrated by figure 7, which is typical of observations to date, and shows 25mm deflection of a 1.2m thick diaphragm wall for a 15m deep excavation in backfill sand and marine clay, compared with a predicted deflection of 35mm. The restraint of the cross walls can be clearly seen, not quite as the design predicts, with more movement at the cross wall/diaphragm wall interface. It is suggested that a perfect interface should not be expected and the design should allow for a small movement at this interface to model the actual conditions more realistically. An additional benefit would be in a reduction of bending moments within the wall profile.

Deep Cement Mixing

Deep cement mixing (DCM) is an old and trusted technique that appears to be gaining a more popularity recently. It involves mixing and removing a portion of the insitu soil by means of a mechanical auger, whilst adding cement to increase the strength of the ground. Dependant upon the proportions and exact material added, the improved ground strength varies but generally numbers similar to JGP can be used. Normally column diameter is smaller than JGP, however recent modifications to the plant utilize multiple augers on one rig giving it the benefit of better construction rates than JGP. An additional significant advantage, during construction, is that the auger provides a clear passage to the surface for spoil removal ensuring that cavity expansion in the ground and heave is controlled. The major drawback of DCM is that full contact between the columns and the retaining system cannot be assured, as a circle is being installed adjacent to a straight end, resulting in windows that treatment cannot cover. The only way to ensure full treatment is to bring JGP plant to install the columns adjacent to the wall, which is time consuming and expensive or look at some form of hybrid system. Another problem faced during construction is that due to the greater auger size, DCM more frequently encounters obstructions within the ground, making it a more suitable method for clear sites. This issue needs to be evaluated based upon the land use history of the site and site investigation prior to its' choice.

Jet Mechanical Mixing

Jet mechanical mixing (JMM) is a hybrid system that combines the benefits of both JGP and DCM. It has been used in Japan and on several projects in Singapore, most notably for the Nicoll Highway Station construction of the CCLP, Osborne & Ng (2008). For this project, the ground treatment option was Jet Mechanical Mixing (JMM), a hybrid of jet grouting and deep soil mixing. A proprietary name, RASJET is given to it by the specialist contractor from Japan, Raito Kogyo. This was the first time such a system had been used in large-scale project in Singapore.

JMM is a combination of soil mixing and jet grouting that produces overlapping columns with an internal column of mixed soil created by the auger and an external column created by a slurry jetting into the in-situ soil. The process of forming the columns is similar to the method of forming JGP columns with the addition of dual and counter rotation mixing blades on the drill rod to ensure intensive soil mixing. Figures 8(a) and (b) show the JMM machines, the drilling rod and the mixing arm of the machine. The rod/auger diameter can be varied, but is generally large, in the range of 450mm as compared to the traditional JGP rod of 200mm. The high stiffness of the drill rod contributes to a more accurate drilling verticality. Combined with the rod are the mixing blades which create an inner mechanical soil mixing column of 1.6m diameter, this can vary dependant on the exact nature of the plant. A jet grout nozzle on the mixing blade introduces cement slurry mix with pressurized air into the soil adding a further 0.6m of jet grouting around the soil mixing column, creating a 2.8m column within the ground. These columns are then designed with appropriate overlap to provide a full coverage of the treated areas.

There are numerous advantages to this system as outlined by Page et al (2006) and Ueda et al (2007), principally the benefits from both mixing and grouting are experienced. From the mechanical soil mixing, a known treated area is assured and from the jet grouting, a sizeable overlap and penetration into any shadow areas close to the retaining system, which cannot be improved by mechanical mixing, is achieved. Heave is not a major issue as there is a path for slurry to the surface, the auger. The major benefit is in the improved strengths achieved. A large number of tested core samples were taken and these were very consistent, demonstrating an average qu of 3690 kPa and E of 572MPa at the JMM level. As the auger was retracted cement was still pumped improving the ground between the treated layer and surface. Two zones were identified, the upper marine clay which was improved to an average qu of 678 kPa and the fill improved to an average of 356 kPa. In terms of the excavation this improved ground had major implications allowing one strut level to be removed and reducing a maximum predicted movement of 80mm to 20mm.

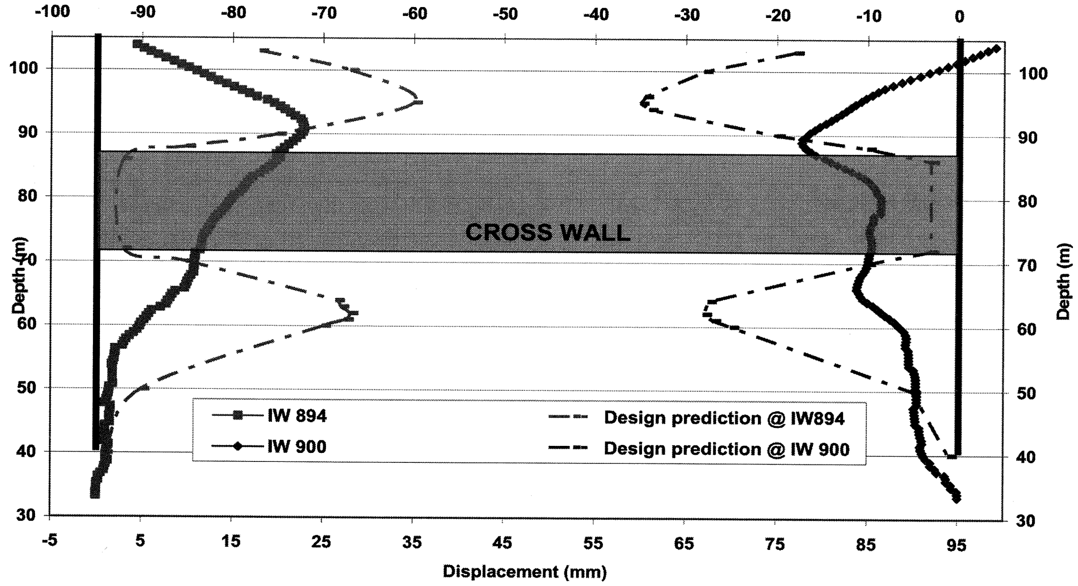
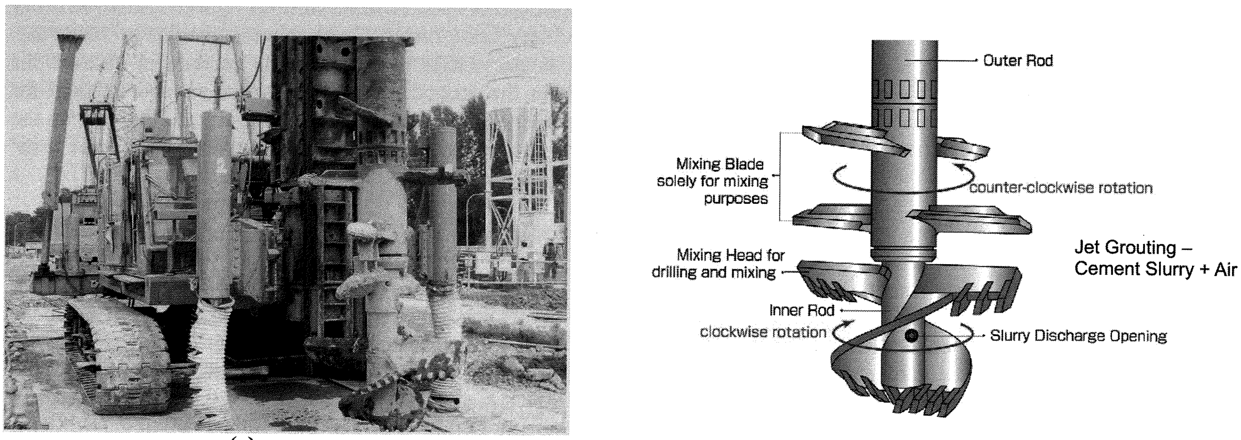


Fig. 7 Cross wall performance: Comparison of Design and Predicted movements



(a) (b)

Fig. 8 (a) JMM machine; (b). schematic diagram of the drilling rod showing the mixing arm of the JMM machine

CONCLUSIONS

The use of ground treatment to successfully meet challenges posed during excavation in the Kallang formation is well documented and understood. From current experience, however, JGP is in danger of being discarded, as workmanship issues are causing problems during construction, resulting in questioning its' ability to produce a complete slab and problems related to heave. The primary reason for this being the inability to control cavity expansion during installation. This is not always the case and when installed properly, which given todays' understanding and technology is eminently achievable, JGP is a very useful tool for construction projects. In fact evidence suggests that if workmanship can be guaranteed there is room for exploring the option to use more realistic, higher design parameters in the design analysis.

Together with JGP, cross walls, JMM or DCM provide a number of flexible solutions for the designer to consider. The many merits of these options, combined with the construction environment need to be considered by the designer in making the choice. This choice is essential to ensuring that risk during the construction phase is minimised. The correct choice combined with following well established installation procedures contributes significantly to the success of the construction phase of the project providing a robust design that can be easily installed in a timely manner. An incorrect one has major implications during construction, varying from structural failure, to program overrun.

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