Conference Technology CONTEC-2001,
Kota Kinabalu, Sabah, 11-13 October 2001

Fill Compaction and Its Consequences of Non-Compliance

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ABSTRACT: Many failures including building failures and road pavement were the results of non-compliance to the compaction requirements of fill for its engineering purposes. The remedies are often very costly and sometimes catastrophic. Many of these failures have been subjected to arbitration and legal suits.

The paper presents the concept of compaction and its requirements for various engineering purposes. It also presents some case histories on the failures related to non-compliance.

1 INTRODUCTION

Soil and rock represent the most abundant and easily available construction material on the earth. These natural materials exist as the supporting medium virtually for most of the civil engineering structures. Due to rapid development, new developments on natural undulating land away from coastal areas and hillsites are being levelled as platform for buildings, roads and etc. As a result, cut-and-fill earthworks are necessary to form the platform for the structures. When filling is involved, it becomes necessary to consider its implications on the structures, in particular when the fill is not properly compacted.

Basic fundamentals of compaction are sometimes not clearly understood by some practitioners, so as the performance of the end products.

Very often, there are different opinions on the achieved engineering properties for fill materials with respect to the specifications adopted in the contract. In many cases, standard specification for road works is commonly used for earthworks with other intended functions, hence leading to unnecessary disputes during the work implementation and the interpretation of test results. It is crucial to capture the important key features and controls in the specification to ensure compliance for the intended functions. For the contractual purpose, there are generally three types of earthwork specifications, namely method specification, end product specification and performance specification, commonly used.

Quality control testing is an important aspect for checking compliance at site. The adopted testing procedures have to be practical and quick for site implementation.

The consequences of non-compliance of earthwork compaction can sometimes be catastrophic.

This paper discusses the abovementioned issues and presents some case histories on failure due to non-compliance.

2 FUNDAMENTALS AND THEORY OF COMPACTION

Compaction is a process to increase the density of soil mass by mechanical means, which usually involves rolling, vibrating, tamping or combination of these processes. Such process is to rearrange the soil particles with expulsion of air in the voids of soil mass without major changes in pore water, except for granular soil, in which water is possible be pressed out. However, water content plays a vital role in compacting process to achieve certain compactness of the soil mass. Higher compactness of the soil skeleton implies higher soil strength, lower compressibility, lower permeability and less susceptibility of other engineering properties to water content alteration. These are the important engineering features of the compacted soil mass.

It is important to distinguish compaction from consolidation, which is a geotechnical process of expelling pore water from the voids as a result of volume reduction under external static loading or the soil self-weight. For unsaturated or partially saturated soil, air will be expelled in the consolidation process.

Using simple relationship between the specific gravity of soil particle, void ratio and moisture content, a series of envelope curves with different air void ratios can be computed and plotted on graph as shown in Figure 1 for a given compaction effort. It is not difficult to understand that lower moisture content in the soil skeleton will result in higher shear resistance between the soil grains during compaction. This is due to high contact stress in the soil grains as a result of high surface tension generated from the meniscus of water between the soil grains. When moisture content gradually increases, the soil skeleton structures will tend to collapse and rearrange easily to a more compact state under compaction as the effect of surface tension reduces with increasing water content. When the dry density of the compacted soil mass reaches a peak, the corresponding moisture content is called optimum moisture content (OMC). Dry density is a good indicator of compactness of soil mass instead of bulk density, which will be altered with the water content. If excessive water is present in the voids of the soil skeleton, the large volume of the incompressible water will act as a retardant, which absorbs and dissipates the compaction energy and therefore results in lower compactness. This simple fundamental can explain why the dry density-moisture curves in most soil types have a peak at the OMC and are curved down at both sides of the peak.

Theoretically, the zero air voids line in Figure 1 means a fully saturated soil mass and no part of the compaction curve can be beyond the zero air void line. However, it is too costly and time consuming to expel all air in the voids of soil mass to achieve fully saturated condition by mechanical compaction practically. Generally, there is also no engineering requirement to do so. Nevertheless, it is possible and practically to achieve the compaction state with acceptable air void by compacting the soil on the wet side of OMC, in which the wet side of the compaction curve is more or less parallel and also closer to the zero air void line.

It should be understood that all compaction curves of a specific soil type are with respect to the amount and nature of compaction energy. For instance, higher compaction energy of same nature will shift the compaction curve to the left and up from its original location. Same energy input but different nature of energy, such as vibratory and static rolling, will also result to different compaction curve. Soil type will also affect the compaction curve. Soils with low plasticity and coarse grains will achieve lower dry density for a given compaction effort as compared to soils with high plasticity and fine grains.

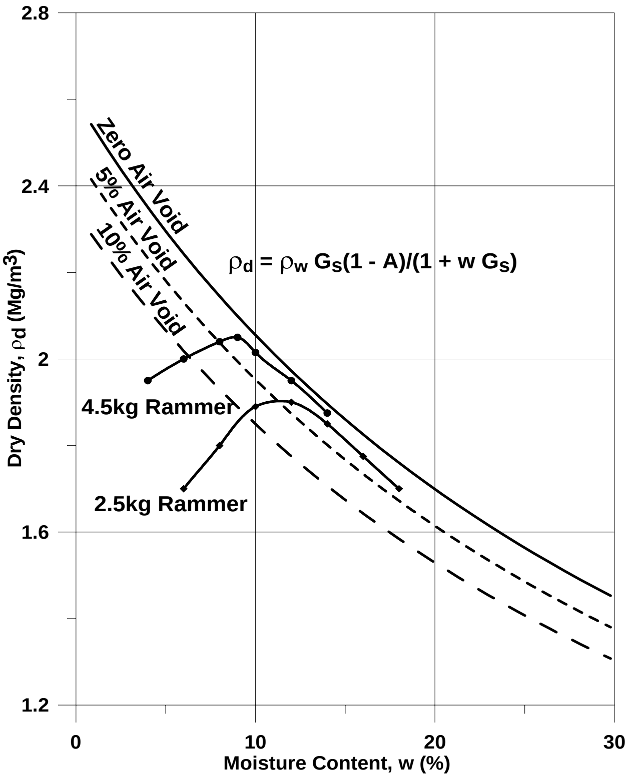

Figure 1 Dry Density-Moisture Content Relationship with Compaction Curves

3 LABORATORY AND FIELD TESTING

In order to quantify the degree of compaction, laboratory test has been established as a reference to compare with the field achievement. However, the procedures of such tests were arbitrarily established during its invention but have now been standardized in the earthworks specification worldwide. The famous laboratory compaction test is Proctor test devised by Proctor (1933), which used mechanical drop rammer to compact the soil in sequence of thin layers within 1 litre cylindrical steel mould. In general, the test results presented in the plot show the relationship between the achieved dry density of compacted soil over the range of moisture contents for a certain compaction effort. Each compaction data point in the plot represents one compaction test at specific moisture content. The compaction curve is the plot of these points and indicates the maximum dry density (MDD) with the corresponding OMC. It should be noted that the compaction curve established from the compaction test may not be necessarily applicable in free draining granular soil, such as sand, in which water can readily be expelled during compaction process and the typical compaction curve would be different. There are two types of compaction tests, namely the "Standard Compaction Test" and the "Modified Compaction Test", which are both defined in Part 4 of BS 1377 : 1990. The major differences between these two tests using the same compaction mould are tabulated in Table 1:

Table 1 Comparison Between Standard Proctor Test and Modified Proctor Test

Standard Compaction Test	Modified Compaction Test
Using 2.5kg rammer ($596kJ/m^3$)	Using 4.5kg rammer ($2682kJ/m^3$)
Rammer Drop: 300mm	Rammer Drop: 450mm
Compact in 3 thicker layers	Compact in 5 thinner layers
BS1377 ASTM D698	BS1377 ASTM D1557

The need to develop the modified compaction test is mainly due to the availability of modern compactor with higher compaction energy rating and also the technical reason for higher MDD. The compaction energy of modified compaction test is about 4.5 times of that in the standard compaction test.

Both tests can be compacted in either one litre steel mould or CBR mould depending on the application of the test results. If CBR test is needed on compacted sample, then CBR mould should be used for compaction and later for CBR test.

During sample preparation, special attention should be given to soils containing particles that are susceptible to crushing. Therefore, soils of such nature should not be reused after compaction tests. BS 1377 : Part 4 provides very elaborative details on this aspect.

For free draining granular soil passing 37.5mm test sieve, dry shaking test and dropping test are more appropriate to establish density index for sands and gravelly soil respectively.

After the MDD and OMC of a specific soil type have been established based on the required laboratory compaction tests, the design engineer will then specify the requirements for field compaction. This will further be discussed in the later section on specifications.

To check the quality and degree of compaction in field, numbers of field compaction tests have been devised with the features of simple and fast operation for reliable and repeatable results. It is important to determine the field dry density (FDD) and also the corresponding moisture content of the compacted soils to compare the computed dry density ratio or the air void ratio with the tolerance limits in the specification for checking of compliance. The most common field dry density tests are sand replacement method and nuclear density gauge of non-destructive nature. In the determination of compacted soil moisture content, the conventional oven dry method is preferred with supplementary indirect field tests using microwave oven or speedy tester. However, proper correlation is required for meaningful application. Plate 1 shows the speedy tester commonly used in earthworks operation.

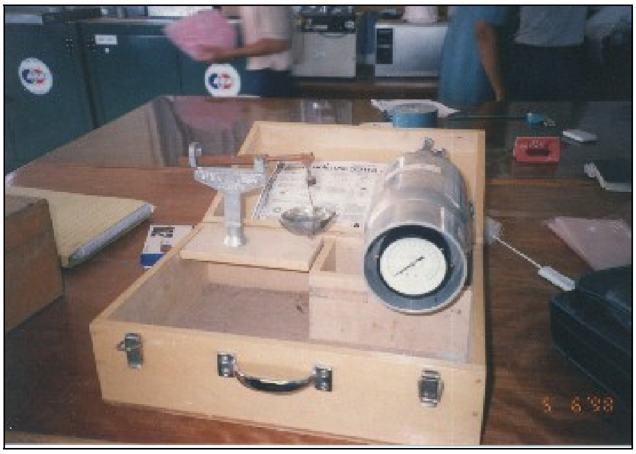

Plate 1 Speedy Tester for Quick Determination of Moisture Content at Site

4 STATUTORY REQUIREMENT

Non-compliance of earthworks often relates to insufficient quality assurance and control by the contractor and inadequate site supervision by the supervising consultant.

Section 71 of the Street, Drainage and Building Act, 1974 does contain a statement in relation to the earthwork compaction. The relevant portion of the statement in the Bulletin Ingenieur (BEM, 2000) is as follows;

"Where any building or part of a building fails, whether in the course of construction or after completion, or where there is any failure in relation to any earthworks or part of any earthworks, whether in the course or after completion thereof and the cause of such failure is due to any one or more of the following factors: (a) misconstruction or lack of proper supervision during construction; (b) misdesign or miscalculation; or (c) misuse of such building or part of such building, or of such earthworks or part of such earthworks, the person responsible for (a) such misconstruction or such lack of proper supervision; (b) such misdesign or miscalculation; (c) such misuse, shall be liable on conviction to a fine not exceeding five hundred thousand dollars or to imprisonment for a term not exceeding ten years or to both (latest update revises the fine from RM50,000 to RM500,000, BEM, 2001).

Building is defined in the Act including any house, hut, shed or roofed enclosure, whether used for the purpose of a human habitation or otherwise, and also any wall, fence. Platform, staging, gate, post, pillar, piling, frame, hoarding, slip, dock, wharf, pier, jetty, landing stage or bridge, or any structure support or foundation connected to the foregoing."

5 SPECIFICATIONS

There are generally three basic types of specifications for compaction of the earthwork , namely;

a. Method Specifications: Specify the procedure for the placement and compaction of the fill, such as type and mass of equipment, the compacting thickness or number of passes and scarifying between compacted layers of fine-grained soils to eliminate lamination.
b. End Product Specifications: Specify certain properties of the fill as placed and compacted, such as the achieved dry density ratio, placement moisture content, air voids, CBR value or undrained shear strength.
c. Performance Specifications: Specify certain aspects of the behaviour of the completed fill, such as maximum settlement over specific period of time after filling.

In Malaysia, the most common used earthwork compaction specification is End Product Specifications. Sometimes, combinations of the abovementioned specifications have been adopted, but usually lead to difficulties in implementation and disputes with contractor.

<u>Dry Density</u>

The dry density ratio, which is the ratio of achieved field density to maximum dry density of either standard or modified Proctor compaction test, is the most common criteria being used in many earthwork specifications. However, the rationale of specifying certain percentage, such as 95% of MDD, may not always be there. Such commonly used percentage is more of the rule-of-thumb basis rather than specially tailored figure for a specific application. There are some guidelines for minimum standard of compaction proposed in AS 1289 as shown in Table 2.

Table 2 Guideline for Minimum Standard of Compaction (AS 1289)

Type of Fill	Minimum Dry Density Ratio *	Minimum Density Index
Residential Fill	95%	65%
Commercial Fill to support floor loading up to 20kPa and isolated pad footing to 100kPa	98%	70%
Road Embankment		
(a) ≥ 0.3m below pavement subgrade	95%	65%
(b) < 0.3m below pavement subgrade	100%	80%

* Note : All dry density ratio relate to Standard Compaction, in accordance with AS 1289 E1.1

Where landscape or other non-load bearing areas are present in the development, it is not necessary to achieve high level of compaction. Therefore, a more lenient compaction specification should be specified to reduce construction cost and time. Nevertheless, this demands a proper site planning during the earlier stage of design development. The deposition of fill of various material types and the corresponding compaction requirement should be clearly specified based on the site zoning for its intended functions.

It is also advisable to specify light compaction on the last layer of compaction lift at the end of the day using smooth-wheeled roller to form a thin and less permeable layer with smooth sloping surface to encourage surface run-off of rainfall. This can reduce erosion by the runoff and protect the lower compacted fill. Scarification of this top smooth lightly compacted layer is required to remove the lamination, particularly for fine-grained soils, before placing the next lift as the lamination provides poor bonding between the two compacting lifts. Plate 2 shows the smooth compacted surface of a fine-grained soil. Plate 3 shows the scarifier.

Plate 2 Smooth Surface of Compacted Soils

Plate 3 Scarifier Mounted to Back-Pusher

For controlling the potential of collapse settlement, it is suggested to limit the air void content not exceeding 5% in addition to the specified dry density ratio (Charles et al, 1998).

It is important to understand the actual requirement before preparing the specifications. Specifications developed for highway embankment may not be appropriate for fills on which buildings will be founded. Building structures are much more vulnerable to ground movement than road and therefore calls for more stringent earthworks specification on building platforms. It is also a bad practice to always base the compaction requirement on the modified Proctor standard just because it is newer or conservative. This will lead to unnecessary extra time and cost for the project. In certain circumstances, over-compaction will not result in satisfactory end product. Whyte, I. L. & Vakalis, I. G. (1987) report that slickensided slip plane in clay fill as a result of over-compaction by pneumatic tyred roller at moisture content wet of OMC at Trenton and Tiber Dams. Sometimes over-compaction will also cause breakage of soil or rock particles, in which the particle grading will be altered. This can have serious implications on altering of compaction characteristics and also changing the filter grading if the compacted material is designed as filter. Plate 4 shows the breakage of rock fragment under heavy compaction. Modified Proctor compaction test should only be specified when high dry density and lower compaction moisture content are desirable.

Plate 4 Breakage of Rock Fragment under Heavy Compaction

Moisture Content

Limits of moisture content during fill placement are also a vital aspect to be specified. If the fill is too wet, there will be risk of excessive consolidation settlement and low strength or, on the other hand, compaction on dry extreme side of OMC, the fill will then be vulnerable to collapse settlement. In general, compaction on wet side will tend to produce fill with plastic characteristics and better deformability whereas brittle fill will be produced with compaction on the dry side, which is unfavourable for earth dam. Conditioning of fill to comply with the specified limits of moisture content around the OMC is sometimes necessary to facilitate compaction and achieve the required dry density.

Loose Lift Thickness

If the loose lifts are too thick, it will result in a dense upper crust overlying less compacted soil. This is true regardless of the type of the used or soil type. The loose lift thickness should be determined such as to allow compaction energy to spread throughout the thickness to promote the specified fill density and low air voids content. Figure 2 shows the difference between the thin and thick loose lift thickness. The lift thickness is also governed by the maximum soil particle size in terms of compactability. If the soil particle size is larger than or closer to the loose lift thickness, the chances of having poorly compacted soil mass are very high, particularly those soils around the large soil particles, such as large rock fragments. Plate 5 shows the poor compaction around a large rock fragment for a rockfill compaction. It is generally accepted that the largest particle size of the compacting soil should not be exceeding two-third of the loose lift thickness for proper compaction.

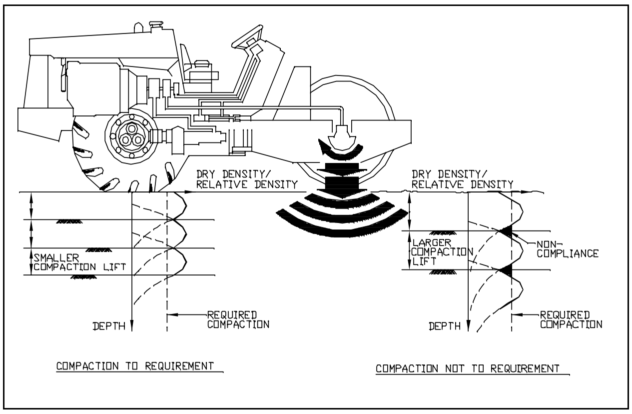

Figure 2 Control of Loose Lift Thickness

It will be beneficial to all parties that a site trial compaction should be conducted to determine compacting thickness, number of passing and the range of moisture content for a soil type in achieving the specified compaction requirements.

Plate 5 Poor Compaction around Large Rock

Testing

Five points compaction curve is generally recommended. One point compaction test should never be allowed due to high degree of uncertainty and variability of compacted materials. For each source of material supplied for fill compaction, separate compaction test should be carried out to establish the reference for field achievement.

The frequency of field quality control testing should be clearly specified in order to have acceptable representative statistics. In Australia Standard AS 3798 : 1990, guidelines and testing frequency are specified as in Table 3. However, if the material types in a compaction are more than one type, then more field density tests are required.

Table 3 Guidelines to Frequency of Field Density Test (AS 3798 : 1990)

Scope of Earthworks	Frequency of Field Density Tests
Large Scale Operation (Industrial lots, Road embankment)	One test per 500m^3
Small Scale Operation (Residential lots)	One test per 200m^3
Concentrated Operation (Gullies filling, Farm dam)	One test per 100m^3
Confined Operation (Filling behind structures)	One test per 2 layers per 50m^2
Trenches	One test per 2 layers per 40m

Trenter & Charles (1996) have presented an useful model specification of engineered fill for building purpose.

6 ASSOCIATED ENGINEERNIG PROBLEMS IN FILL COMPACTION AND CONSEQUENCES OF NON-COMPLIANCE

The engineering problems associated with fill compaction are as follows:

a. Total/Differential Settlements due to fill self-compression result in downdrag on foundation piles and alteration of drainage gradient.
b. Collapse Settlement upon wetting of compacted fill.
c. Weak Strength
d. High Permeability of Fill

Some useful details for monitoring negative skin friction on circular spun pile are given in a technical paper by Gue et al (1999). Charles & Watts (1996) and Charles et al (1998) have presented the potential of collapse settlement in fill material and also the adequacy and appropriateness of fixing the 95% of standard compaction effort for engineered fill in relation to collapse settlement.

In the earthworks design, the needs of specifying compaction requirements are to answer the above highlighted engineering problems.

The consequences of non-compliance will be demonstrated in the following cases histories.

6.1 *Case One : Excessive Foundation Settlement & Short Piles*

This case involved some 40 units of single-storey terrace houses and 70 units of double-storey terrace houses, in which platform settlement and structural cracking were observed. Plates 6 and 7 show the voids underneath the ground beam and the cracks at the ground beam respectively after fill settlement.

The affected buildings were on filled ground of varying depths up to 20m overlying the undulating meta-sedimentary formation. The platform was mostly filled using the cut materials with significant content of boulders, which subsequently posed problems to pile installation. The existence of boulders in the fill has been confirmed during the additional subsurface investigation, in which a trial pit done indicated that a boulder of about 1m in size was discovered. The subsurface investigation also revealed that the platform was not properly compacted to the normal standard of engineered fill.

Plate 6 Voids underneath Ground Beam

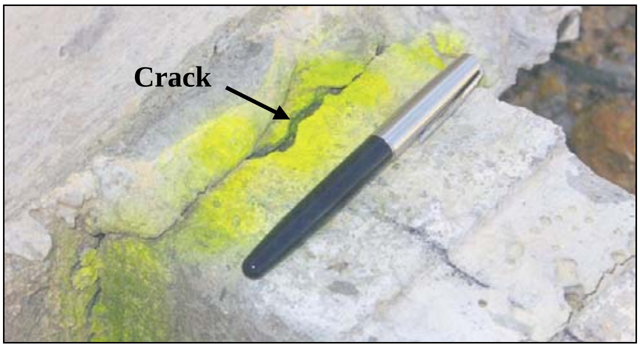

Plate 7 Cracks on Ground Beam

Excessive platform settlement occurred a few months after completion of the earth filling and causing serious structural cracks on the newly constructed ground beams, stumps, ground floor slabs and the structural frames. More serious distresses were observed at units on thicker fill. Crack gauges and settlement markers were installed during the investigation by the authors to monitor the changes of crack width and platform settlement with time respectively. The results of monitoring confirm the settlement and cracks were active. The observed crack pattern on the wall was mostly diagonal and initiated from the corners of the door and window openings that were the areas of stress concentration when distortion of the structures occurred. Cracks on the structural frames were mainly located at the beam-column connection and the mid span of the beams, which have maximum flexural stresses.

6.2 *Case Two : Platform Settlement and Wall Collapse*

This case history was featured with many geotechnical failures in the infrastructure works and the buildings. The project site was located at a previous rubber estate with undulating terrain of meta-sedimentary formation and a few numbers of natural water streams within the project site. As the development area was very large in lateral extent, the earthwork design concept was based on cut and fill balance and to minimize rock excavation as bedrock was commonly expected at shallow depth below the undulating original terrain and has a fairly consistent weathering profile. Therefore, the earthwork platform was finally completed with varying fill thickness and earth cutting. The maximum fill thickness in this area was about 32m. Unfortunately the filling areas were not properly compacted as engineered fill. Many problems were subsequently surfaced up as a result of fill settlement, which was largely attributed to poor compaction and collapse compression after saturation with prolonged rainfall and rise of groundwater level.

There were about 200 units of double-storey terrace houses in one of the development phases suffering from significant fill platform settlement. These buildings were supported on 125mm×125mm timber piles. The non-suspended ground floor slab became suspended after the platform settled and caused the ground floor slab to sag. The partial friction between the four sides of the floor slab and the ground beams restrained the slab from settling. Figure 3 shows the schematic diagram of the sagging ground floor slab and Plate 8 shows the settling floor slab. Voids underneath the ground floor slab was suspected during final finishing of the floor tiles and was further confirmed after hacking the suspected slabs for inspection as shown in Plates 8 and 9. The maximum gap between the center of the sagging slab and the settling fill platform as measured at site was about 150mm. Therefore, the total settlement of the platform at the time of investigation was estimated to be about 225mm, assuming the buildings did not settle. The pattern of platform settlement coincided very well with the original topography, in which larger platform settlement occurs at the thicker fill areas.

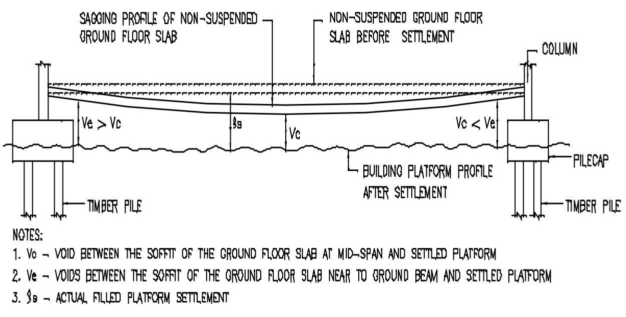

Figure 3 Sagging Ground Floor Slab

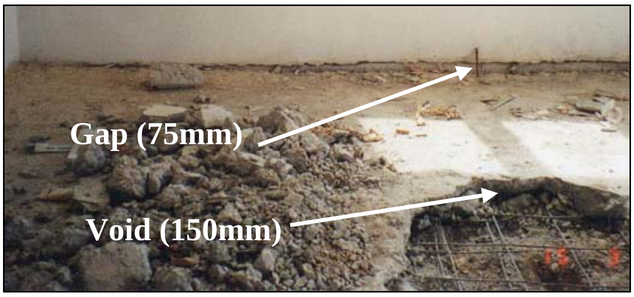

Plate 8 Sagging Ground Floor Slab

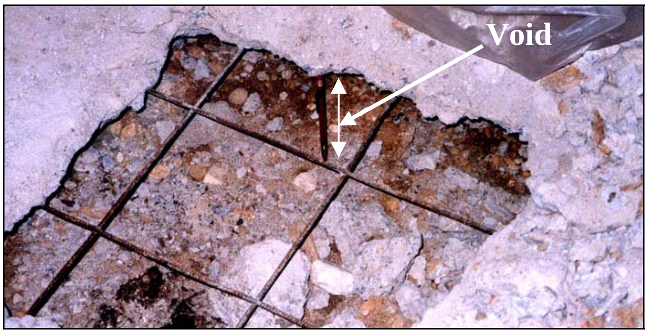

Plate 9 Void underneath the Ground Floor Slab

Another concern of the associated platform settlement was the potential negative skin friction developed at the piled foundation, although at the time of investigation there were no serious distresses or settlement observed on the structural frame except some vertical tension cracks between the units on split levels platform. The review of the topography survey of the affected units and the piling records reveals that some of the installed foundation piles terminated within the fill and some penetrated few meters into the original ground. It appeared that the piles were installed to predetermined length. The telltale sign of the vertical tension cracks on the external walls of buildings on different platform levels had indicated potential future excessive differential settlement at areas where piles were installed within fill of varying thickness. For those piles penetrated into original ground, predominantly end bearing condition could be expected, in which negative skin friction due to platform settlement could overstress the foundation piles beyond the allowable design stress level of the piles but this has yet to reach structural failure at ultimate limit condition or showed any excessive settlement. Figure 4 shows some pile penetration records in both fill or cut ground and reveals that the foundation piles were likely to be installed to length instead of following the normal piling practice based on static calculation from the soil properties, profile and normal driving control using appropriate set criterion.

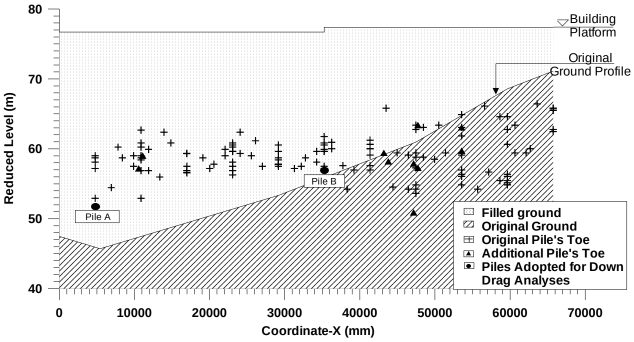

Figure 4 Pile Penetration Records

A collapse of retaining structure was also observed at the site. The retaining structure was about 3.5 m high pile supported rubble wall to retain earth at the backyard of few units of apartment structures on piles. The rubble wall was supported on two rows of piles from 15m to 24m long at pile spacing of 3.7m. At the toe of rubble wall, there was a large monsoon drain of 6m wide and 3m high. Figure 5 shows the cross section of the rubble wall and the monsoon drain. Plate 10 shows the picture of the completely collapsed rubble wall and the RC drain section. Most of the platform of these units was constructed over the previous natural stream by earth filling. The maximum thickness of fill was about 25m. The failure occurred during the monsoon month with frequent heavy raining. The preliminary finding on the cause of the collapse was mainly due to the brittle behaviour of the rubble wall when subjecting to differential distortion along the wall as a result of fill settlement. The slab supporting the rubble wall was believed to be initially designed as a seating plinth for the rubble wall, but the piles was subsequently provided with the objectives of avoiding settlement and to provide a better support to the rubble wall.

However, due to the brittle behaviour of the rubble wall, the wall cracked even at very small distortion between the piles and the unsupported mid span of the plinth after the platform settled. Once the wall cracked, the stones initially binded by the cement mortar became loose mass of stones and collapsed. Plate 11 shows the cracks of rubble wall due to such distortion.

The collapsed mass piled up and surcharged the RC monsoon drain sections causing subsequent bending failure at the wall-base connection of the section. The detailed analyses indicate that the monsoon drain had sufficient resisting capacity to retain the backfill if the rubble wall was intact. The collapse had triggered retrogressive instability failure of the retained platform to the units of adjacent houses. However, there were no obvious distresses yet on the building.

Plate 10 Collapsed Monsoon Drain

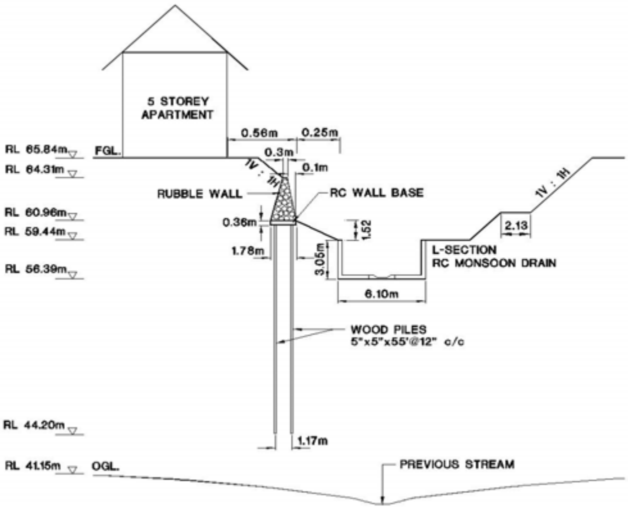

Figure 5 Cross Section of the Rubble Wall and Monsoon Drain

Differential settlement of filled platform could also cause distresses to the infrastructure works. Plate 12 shows the shear cracks with the whitish calcite deposits on a cast-in-situ reinforced concrete (RC) monsoon drain due to differential fill settlement. Figure 6 shows the schematic diagram on the cause of the shear cracks in association with the uneven fill settlement.

Plate 11 Shear Cracks on Rubble Wall

In certain conditions, changes of platform level due to differential settlement as a result of varying fill thickness can potentially lead to a very unfavourable drainage pattern, leading to a failure. Plate 13 indicates the serious erosion of a completed platform of the industrial lots. The area of erosion is the location of previous stream with fill over it. From the site observation, it is evident that depression was formed around the previous valley where the former stream was located. Theis depression forms a perfect collection point for surface runoff and channelise the runoff to a constrict flow running towards the edge of platform. Unfortunately, the intercept drain is not properly maintained and silted up. As a result, the surface runoff has chosen to flow over the berms and erode into gullies. These gullies initiated from the constricted flow on the platform eventually form a natural earth drain and damage the monsoon drain. Plate 13 shows the failure of monsoon drain due to erosion.

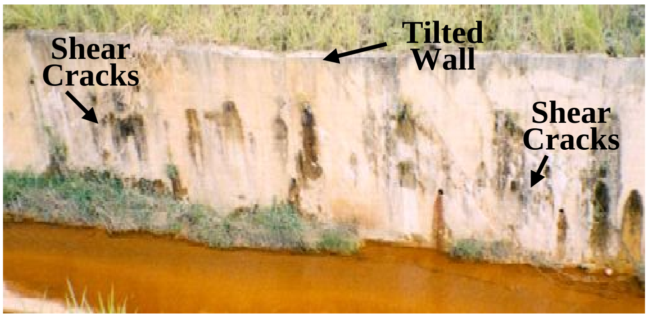

Plate 12 Shear Cracks on Monsoon Drain

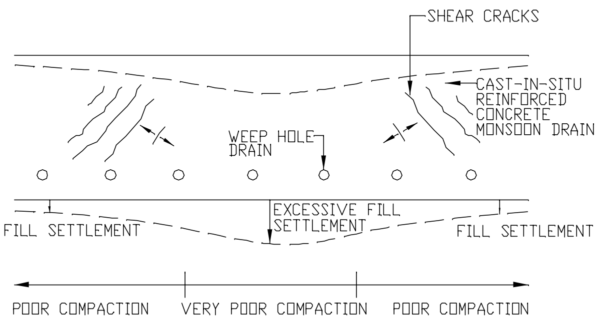

Figure 6 Shear Cracks on Monsoon Drain

Plate 13 Erosion Failure of Monsoon Drain

6.3 *Case Three : Distortion of Building*

This case history was featured with excessive distortion of the two-storey terrace structures due to differential settlement between the fill of varying thickness and the cut ground. Due to the uneven settlement of the platform across the longitudinal axis of the terrace structures, diagonal tension cracks were developed on the structural frame and walls. A ϕ150mm asbestos concrete water pipe was also damaged and leaked due to the differential settlement. The leaking water subsequently saturated the fill material and initiated collapse settlement and further aggravated the distortion. Figure 7 shows the schematic diagram of the failure and the failed slopes is shown in Plate 14.

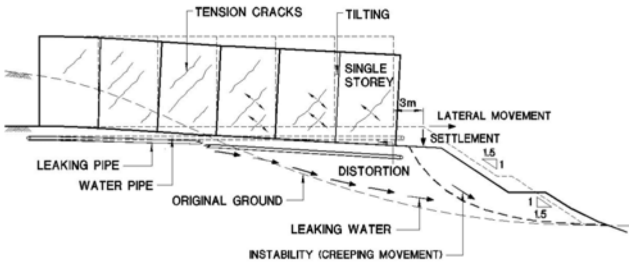

Figure 7 Building Distortion due to Differential Fill Settlement

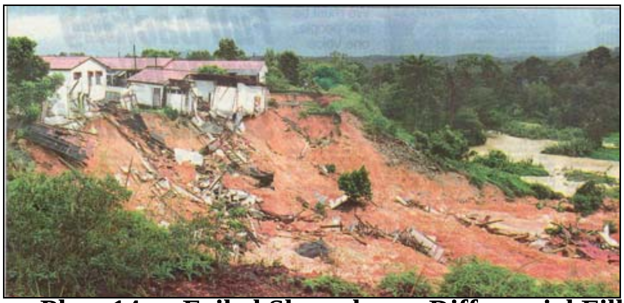

Plate 14 Failed Slope due to Differential Fill Settlement

6.4 *Case Four : Differential Settlement at Bridge Abutment*

This case history shows the differential settlement behind a bridge abutment in Pulau Batam, Indonesia. It can be understood that proper compaction at a confined areas is difficult. As a result, the settlement between the fill sitting on sedimentary bedrocks and the piled structure forms a depression, which affects the riding comfort and can also pose danger to vehicle passengers as the tyre resistance may temporarily detached from the depressed pavement. Plate 15 shows the depression behind the abutment.

Plate 15 Differential Settlement behind Abutment Fill

7 CONCLUSIONS AND RECOMMENDATIONS

It is very clear that fill compaction has important impact on development with fill ground. If not properly addressed during the early stages of project implementation, the consequences can be catastrophic and costly. This has been demonstrated in the few case histories presented in this paper.

The following recommendations are given to prevent and mitigate the non-compliance:

1. It is important to carry out necessary compaction tests on each type of material sources to establish the target reference for field compaction achievement.
2. The design engineer should only specify the actual required compaction effort rather than over-specifying for extra unjustifiable comfort. Sometimes, over-compaction can cause unexpected problems, such as generating slickensided slip plane and altering particle grading of compacted soil due to particle breakage.
3. The loose compaction lift should be specified to ensure minimum dry density within the compacted lift based on the performance of trial compaction for specific compaction equipment.
4. There is a need to limit the largest particle size to ensure proper compaction and uniformity of the compactness of fill.
5. It is important to control the range of moisture content to achieve the target dry density under specific compaction effort. Sometimes, conditioning of the fill materials is required to control appropriate moisture content at placement and compaction.
6. Light compaction to form thin impervious layer using smooth-wheeled roller should be carried out on the last compacted lift at the end of the day to facilitate surface runoff of night rain. Scarification of the smooth compacted surface between lifts in fine-grained soils should be carried out to eliminate lamination and poor bonding.
7. Field tests of statistically representative quantity should be carried out to check for non-compliance. Guidelines of testing frequency have been given.
8. Supervision of compaction should be enforced for any earthworks operation, not only to satisfy the law but also to ensure compliance as it has significant effect to the subsequent construction works.

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