Innovation in earthwork practices

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Abstract Site Earthworks specifications by various authorities have not seen much changes over the last 50 years. However, knowledge and practice relating to earthworks compaction, quality control testing have developed albeit empirically over the last 30 years in different industries such as civil infrastructure, mining and oil and gas, often driven by the need for improvisation or lack of adequate “conforming materials” as per traditional specifications. This paper presents the author’s experience and research in earthworks placement and compaction, development of new tools for quality control of earthworks and how earthworks can be engineered to specific situations focus on High Impact Energy Dynamic Compaction (HIEDYC). Case histories from Malaysia and overseas are presented along with discussion of the benefits to owners. These benefits include fast earthworks procedures with quick validation processes.

1. Introduction
Earthworks are engineering works created through the moving of massive quantities of soil or rock. The process of earthwork includes the excavation of the existing land to a suitable level and the compaction of the fill materials to the appropriate level.

The earthworks specifications from various authorities in last 50 years have not changed much. In the meantime, knowledge and practice relating to earthworks compaction, quality control testing has developed albeit empirically over the last 30 years in different industries such as civil infrastructure, mining and oil and gas, which are often driven by the need for improvisation or lack of adequate “conforming materials” as per traditional specifications. Construction industry needs innovation in earthworks practice including fill placement and compaction. The development of in-situ testing and instrumentation has enabled project timelines to be expedited.

2. Observation of Traditional Earthworks and Related Specifications
Earthworks practices and related specifications have changed very little over the last 50 years.

2.1 Site Clearing
The beginning of earthworks is site clearing works. This involves the removal of trees, demolishing buildings, removing all old underground infrastructure, any other obstacles that might affect the construction process in the future or hinder the project to be done.
2.2 Cutting and Filing
Cutting and filling is the process of moving earth from one place to another to prepare platforms to the design levels. A ‘cut’ is made when earth is cut from above the desired ground height and a ‘fill’ is when earth is used to fill a low point or valley to desired ground level. Cutting and filling is a common technique used to create an even ground surface.

2.3 Proof Rolling
Proof rolling is carried out for the following purposes;
- Identify loose or unsuitable material pockets before fill is placed
- Assess compaction to check if there are uncompacted areas on finished platforms before placing foundations of pavement layers

It is to be noted that the Proof Rolling equipment must be selected based on the expected CBR of the surface to be rolled. For example, if the subgrade material to be proof rolled is expected to have a CBR of 3% then the proof rolling equipment will need to be lighter than the Proof roller used for a subgrade expected to have a CBR of say 10%. These matters are seldom considered in earthworks specifications. If this is not considered in proof rolling, unnecessary disputes might occur [5]. The Texas Department of Transport (TDT) have issued a Technical Advisory: Proof Rolling and Base Curing Advisory states that the purpose of proof rolling is not to establish soil strength, but to assure that the subgrade soil will provide uniform pavement support [10].

Infra Tech Pty. Ltd. (ITPL) resolved such issues on a project where the plastic clay fill was to be compacted at optimum moisture content (OMC) to 98% Standard Compaction. The fill had OMC in the range of 20% to 25% and Plasticity Index in the range of 40% to 60%. Then the 4 days soaked CBR was in the range of 2% to 3%. The compaction was checked by proof rolling with the Australian Standard 3798 Bulk earthworks Specifications (AS 3798) specified truck and failed. When proof rolling was done as per Table 1, and Figure 1 below the CBR 2% to 3% fill proof rolling was found to be adequate [10 and 12].

An example of suitable Proof rolling requirements by Texas Department of Transport (TDT) is shown below in Table 1 below.

Table 1. Proof Rolling Guide (TDT, 2001).

| Well Graded Soils | Poorly Graded Soils |
|-------------------|---------------------|
| Relative Subgrade Support | Poor | Fair | Good | Excellent |
| Stress Level | Minimum | 1 | 2 | 3 | 4 | 5 | Maximum |
| Load (tons) | 30 | 34 | 38 | 42 | 46 | 50 | 50 |
| Tire Inflation pressure (psi) | 40 | 50 | 60 | 70 | 80 | 90 | 130 |
2.4 Traditional Earthwork and Related Specifications
During conventional compaction, moisture content is an important consideration especially for fine-grained or cohesive soils, as it dictates the response of the soil to compaction and associated movements affected by climate or loading. Optimum Moisture Content (OMC) is defined as the moisture content at which the maximum dry density of soil can be achieved for a given compactify effort. When a fine-grained/cohesive soil is significantly below the OMC, compaction is less effective due to frictional and capillary forces within the soil (ASTM stock number: MNL70, 2011).

Current practice for compaction revolves around the OMC to achieve the best results (BS 6031:1981). However, to ensure that OMC is maintained within the material during compaction, significant volumes of water may be required. Alternatively, in wet weather the fill will need to be dried before achieving optimum compaction. This may require consideration of economic, practical and environmental factors.

Conventional compaction relies on Proctor’s (1933) principle (ASTM stock number: MNL70, 2011);
1. Energy used for compaction
2. Water / moisture content of the soil
3. Soil properties

The moisture content at which the maximum dry density is achieved is known as the Optimum Moisture Content (OMC) (see Figure 1). This implies that, to ensure effective compaction, the soils must be kept at the optimum moisture content during compaction. Compaction is generally evaluated by means of degree of compaction, which is calculated as a ratio of the measured field density to the maximum laboratory density. However, if the compactive effort is higher than the OMC can be lower as illustrated in Figure 1 below.

![Figure 1. Relationship between compactive effort and optimum moisture content.](image)

The compaction requirements as well as the compaction plant will vary based on the type of soils used for the fill or in the cut subgrade. These are covered in many earthworks specifications and manufacturers hand books (7). Using conventional compaction plant, the layer thickness for fill is normally limited to 300mm loose thickness. In some instances, with heavier vibrating compactor 450mm thick lifts are possible. A maximum lift thickness of 300mm, means that large particles (greater than 37.5mm in size) cannot be accepted in the fill. This will require crushing and screening of fill with large particles and increase the cost of earthworks.

In cohesive soils if over compaction occurs either due to excessive number of passes or a heavier than required compactor, then loss of strength occurs. This means the compacted clays will become weaker. This must be borne in mind by Engineers and Contractors, since soils on a site are expected to be variable it is necessary to have field compaction trials whenever changes in the type of fill material is observed. This phenomenon is not very pronounced in sandy soils. Hence it is important to conduct filed compaction trials for each project or whenever fill type changes in a project.
3. HIEDYC for Deep Lift Compaction in Major Earthworks

HIEDYC plant can be sued for the following:

- Proof rolling of natural ground before fill is placed
- Fill compaction in layers of 1m to 3m (depending on type of fill material and HIEDYC plant used)

3.1 Proof rolling by HIEDYC

High Impact Energy Dynamic Compaction (HIEDYC) can also be used as a proof rolling equipment to identify the presence of loose or uncompacted ground to a greater depth than the conventional smooth drum vibratory roller because of the high energy imparted. The impact of the heavy mass transfers enough energy to achieve medium compaction to a depth of several meters. In addition, HIEDYC can reduce the risk of differential settlement and can achieve proofing to greater depths, typically 2m to 4m, than with conventional methods.

![Figure 2. Proof Rolling on soft soil site prior to fill placement.](image)

3.2 Deep Lift Compaction of fill by HIEDYC

Method of earthworks compaction by Deep Lift Compaction allow filling to be done in 1500mm to 3000mm thick layers compared to conventional 300 mm thick layers. The most important is filling can be placed at natural moisture content significantly drier of the optimum moisture content without additional water. This is possible due to the significantly higher (up to 10,000 times) energy that this applied by this compaction method. Therefore, the result is a stronger fill that can be placed more rapidly as compared to conventional compaction methods.

The HIEDYC deep compactor has non-circular compaction modules and is towed by a prime mover shown in Figure 3. The HIEDYC modules impart energy vertically downward as a compressive wave into the ground. The validation testing utilising Plate Bearing Test (PBT), Light Weight Deflectometer Test (LWDT) and Deep Cone Penetrometer (DCP) are used as a quality control to validate the deep lift compaction using HIEDYC.

Conventional compactors are capable of compacting clays in 200mm thick lifts and sands in 300mm thick lifts, with moisture levels maintained at or near OMC while HIEDYC can compact most types of soils in loose thicknesses of 1m to 2.5m at natural moisture content. These thicknesses vary depending on the soil types, compaction conditions and compaction requirements. This process of compaction in thicker (than conventional) layers is termed Deep Lift Compaction [4]. an example is shown in Figure 4.
Table 2. HIEDYCTM modules, capabilities and applications.

| Module | Number of sides | Mass (tonnes) | Compaction depth limitations (m) | Mining engineering applications | Civil engineering applications |
|--------|----------------|--------------|----------------------------------|---------------------------------|--------------------------------|
| Tria   | 3              | 17           | 5                                | Pit floors/rock crushing, haul roads, soil dumps, rock dumps, tailings consolidation and strengthening. | Subgrade compaction, earthwork compaction, coarse sand and silt compaction and clay soils in conjunction with Prefabricated Vertical Drains |
| Qadra  | 4              | 14           | 2                                | Haul roads, soil dumps, tailings consolidation and strengthening. | Subgrade compaction for road pavements, earthwork compaction and sand and silt compaction not greater than 1.5m |
| Penta  | 5              | 16           | 3.5                              | Pit floors/rock crushing, haul roads, soil dumps, rock dumps, tailings consolidation and strengthening. | Subgrade compaction, earthwork compaction, coarse sand and silt compaction and clay soils in conjunction with Prefabricated Vertical Drains |

The advantages in the use of Deep Lift Compaction are listed below.

- Layer thickness of fill is 1.5m to 2m thick as against 300mm thick layers used in conventional rolling.
- These 1.5m to 2m thick layers are compacted at the natural in place moisture content and therefore, there will be no need for large quantities of compaction water - as would be required for conventional earthworks - which is not only difficult to obtain but can be very expensive. This leads to environmental benefits.
- Because of larger layer thickness it is also possible to use fill containing particle sizes of 300mm where as in conventional earthworks in 300mm layers, the fill cannot have particle sizes more than 37.5mm. this reduces the cost of reprocessing excavated fill to smaller sizes of less than 37.5mm.
- Quality control is performed using Light Weight Deflectometer Test (LWDT) which provides on the spot results rather than traditional tests where at least 24 hours of waiting may be required. (alternatively, DCP testing or MP testing can also be performed with or without Plate bearing tests to correlate the readings)
- The earthworks completion time can be slashed by more than half, this would mean a reduction of several months off the construction schedule.
- The compacted earth platform will be stronger (can be up to about 3 times the required bearing capacity) which means the foundations cab be (re) designed to be more economical.
- The emissions associated with deep lift compaction are less than 20% of emissions from conventional compaction techniques.
Figure 4. Deep Lift Compaction of gravelly clay.

A comparison of productivity between conventional compaction and HIEDYC compaction is summarised in Table 3 below.

### Table 3. Comparison of productivity between conventional compaction and deep lift compaction of earthwork fill placement (Nathan 2010).

| Technique | Compaction volume per 10-hour shift (m³) | Mode of compaction | Types of machinery | Number of equipment involved | Number of operators involved | Type of QC testing required | Water usage |
|-----------|----------------------------------------|--------------------|--------------------|----------------------------|----------------------------|-----------------------------|-------------|
| HIEDYC deep Lift compaction using HIEDYC TRIA or HIEDYC Penta module in 1.5m to 2m layer thickness a natural moisture content | Varies between 8,000 m³ to 10,000m³ | Earth spread in 1.5m to 2m loose layers at natural moisture content | HIEDYC | 1 | 1 | LWDT, MP, PSP, DCP, EFCPT, Limited PBT for every 1.5m to 2m layers | 100 to 200m² as surface spray for dust suppression |
| | | | Grader to level ground | | 1 | 1 | | |
| | | | Water cart (20,000 litres capacity) | | 1 | 1 | | |
| Conventional compaction using a 12tonne vibratory compactor, to match production of Deep Lift compaction by HIEDYC | 2,500 m³ to 3,500 m³ | Earth spread in 200mm to 300mm layers at OMC | Compactor | 8 to 10 | 8 to 10 | Laboratory MDD and Field Density testing for every 300mm layer | 1,000 to 2,000cu.m depending assuming dry weather and addition of at least 5% by weight of water |
| | | | Water cart | 6 to 8 | 6 to 8 | | |

*Elastic modulus was back calculated from Falling Weight Deflectometer (FWD) results on subgrade.*

### 4. Rapid Testing Methods

Validation tests including Plate Bearing Test (PBT), in-situ CBR test, and Mackintosh Probe (MP) test can be carried out to validate the performance of the ground improvement works. In addition, seismic refraction or surface wave measurements (Multi Channel Analysis of Surface Waves - MASW) are very useful to assess existing ground conditions as well as ground improvement during HIEDYC.
Figure 6 shows the relationship of seismic wave velocity versus the number of HIEDYC compaction runs for a trial area of the reclamation sand fill at Westport, Malaysia (Infra Tech, 2004) [8]. The data for Figure 6 below was collected from a field trial of HIEDYC compaction to establish optimum number of passes for site sub-soils.

The magnitude of the project, type of loads, the structures to be supported and the settlement acceptance limits for structure are influenced by the frequency of testing. As an indication, on large projects a test for every 500m² interval is considered appropriate for important structures and one test for every 1,000m² is appropriate for more settlement tolerant structures.

![Figure 6](image)

**Figure 5.** The relationship of seismic wave velocity versus the number of HIEDYC compaction (passes).

Most empirical requirements for compacted densities have been derived from experience in civil projects. There is very little evidence that high levels of bearing capacity or elastic modulus can be obtained with fills compacted conventionally, especially when the fill is supporting houses on shallow foundations or heavy structures such as factory machinery or mine infrastructure. Furthermore, most density testing approaches have been developed for soil size particles which are less than 37.5mm in size. However, in the mining sector oversize and heterogeneous fill are very common. Conventional density testing cannot be applied to such situations. It may be more appropriate to move away from the conventional approach of density testing in specifications. The use of performance-based earthworks specifications allows for flexibility in the fill materials and the earthworks. With the use of PBT, LWDT, DCP and MASW compaction or foundation preparation can be validated and direct strength parameters can be obtained rapidly and economically.

![Figure 6](image)

**Figure 6.** LWDT result after HIEDYC compaction of approx. 1.5m thick general fill (clayey sandy GRAVAL) loosely placed on HIEDYC compacted foundation (ITPL, 2012c).
Figure 6 above shows how LWDT can be used to assess the optimum number of passes during Deep lift Compaction using HIEDYC modules. Figure 7 shows the LWDT equipment in use on sites.

![Image](image_url)

**Figure 7.** Light Weight Deflectometer Test (LWDT).

5. **HIEDYC deep compaction for loose soils in lieu of excavate and replace in layers**

The HIEDYC Deep Compaction can be used in many ground conditions, ranging from silts, loose sand, gravel, sites comprising of mixtures of different types soils such as landfills. In addition, for sites with soft clays HIEDYC can be used in combination with prefabricated vertical drains (DYCON method) to improve these sites.

The traditional approach to deal with loose or soft layers has been to remove these layers and replace with suitable fall and compact in 300mm layers until, adequate compaction is achieved. Alternatively, piled foundations can be provided for structures on loose layers. All these approaches are costly. In contrast, in situ improvement of existing loose layers by HIEDYC deep compaction has proven to be a cost-effective solution. Subject to the limitations of improvement depth being in the range of 1m to 5m.

The traditional “cut, replace and compact in 300mm layers” type solutions involve a considerable amount of excavation, handling and re handling, disposing of materials and all other activities associated with cutting and replacing. These activities lead to higher costs, time, and issues arising in relation to occupational health, safety and environmental emissions. These factors are often the catalyst to look into alternative methods of ground improvements that are more cost effective, safer and environmentally friendly. A comparison of HIEDYC deep compaction and “cut, replace and compact in 300mm layers” method is provided in Table 4.
Table 4. Comparison of productivity between HIEDYC compaction ad ”excavate, replace and compact in 300mm layers” (Caterpillar performance handbook, 1999).

| Technique | Compaction volume per 10 hour shift (m³) | Mode of compaction | Types of machinery | Number of equipment involved | Number of operators required | Type of QC testing required | Water usage |
|-----------|------------------------------------------|--------------------|--------------------|----------------------------|-----------------------------|-----------------------------|-------------|
| HIEDYC in situ deep compaction | 10,000 Existing materials in situ | HIEDYC | 1 | 1 | LWDT, PSP, DCP, EFCPT, Seismic Survey and Limited PBT for every 1.5m to 2m layers | 200 m³ to 300m³ as surface spray for dust suppression |
| | | Grader to level ground | 1 | 1 | | |
| | | Water cart (20,000 litres capacity) | 1 | 1 | | |
| ”excavate, replace excavated soil in 300mm layers with conventional compaction at OMC” | 3,500 Imported materials in 300mm layers | Trucks | 5 | 5 | Laboratory MDD and Field Density testing for every 300mm layer | 1,000 m³ to 2,000m³ depending assuming dry weather and addition of at least 5% by weight of water |
| | | Excavator | 1 | 1 | | |
| | | Wheel loader | 1 | 1 | | |
| | | Smooth drum or vibratory roller | 8 | 8 | | |
| | | Water cart (20,000 litres capacity) | 5 | 5 | | |

6. Summary
Proof rolling is an essential part of earthworks and must be specified by considering the type of soils to be proof rolled. Fill can be compacted in layers thicker than 300mm as has been practiced for more than 40 years. Deep lift Compaction in layers of 1.5m to 3, thickness using HIEDYC can create higher strength, use less diesel, less compaction water. The high strength can be validated rigorously by seismic wave measurements, LWDT, Plate Bearing, Mackintosh Probe or Dynamic Cone Penetrometer. Small areas where HIEDYC plant cannot run at speeds of more than 8km per hour are not suitable for HIEDYC compaction. Field trials need to be done to establish the optimum number of passes to avoid under or over compaction. This is applicable to both conventional earthworks as well as HIEDYC compaction.

7. References
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