# The specification of fills to support buildings on shallow foundations: the "95% fixation"

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## Summary

Engineered fills which are used to produce suitably shaped landforms for residential and commercial developments need to be constructed to high standards to minimise the possibility of post-construction ground movements causing damage to property built on shallow foundations. The specification and control of the placement and compaction of the fill is a key factor in the successful execution of such projects. This paper examines the link between the ground movements which occur subsequent to building and the state of the fill as compacted. The fundamental significance of collapse compression on inundation is emphasised and the shortcomings of specifications based on an arbitrary compaction standard of 95% relative compaction are illustrated.

## Introduction

In many countries engineered fills are being increasingly used to produce suitably shaped landforms for residential and commercial developments. The fills need to be constructed to high standards to minimise the possibility of post-construction ground movements damaging property built on shallow foundations. The specification and control of the placement and compaction of the fill is a key factor in the successful execution of these developments. The placement and compaction of clay fill for a residential development are shown in **Figure 1**.

The specifications which have been used for most engineered fills for building purposes in the United Kingdom have been based on specifications developed for highway embankments. However, there are important differences between fills for highways and fills placed to support buildings and this approach has not always produced satisfactory results for the following reasons.


**Figure 1: Earthworks for a major residential development: (a) clay fill being tipped**

**(b) clay fill being spread**

**(c) self-propelled compactor**

- **Technical inadequacy of the specification**

The criteria for fills for building developments are more critical than those for highway embankments because there are often severe restrictions on acceptable movements and so specifications developed for highway works are not necessarily adequate for fills on which settlement sensitive buildings will be founded. Furthermore, the Department of Transport earthworks specification is quite complex and has often been reproduced in an over-simplified form.

- **Inadequate quality control**

Highway schemes are often large civil engineering projects which are let to a major contractor and supervised by a consulting engineer both of whom will have substantial earthworks experience. In contrast, engineered fills for buildings are often relatively small in scale being of shallow depth and restricted lateral extent. The work is unlikely to be executed by a major contractor and the consulting engineer, if one is employed, may not be experienced in compaction work.

- **Inappropriate compaction equipment**

A highway scheme is normally of such a size that the compaction equipment necessary to fulfil the requirements of a method specification can be obtained without difficulty whereas specific types of compaction equipment may not be readily available for small residential and commercial developments.

This paper examines the link between ground movements which occur subsequent to building and the state of the fill as compacted; the fundamental significance of collapse compression on inundation is emphasised. Specifications have often been based on an arbitrary compaction standard of 95% relative compaction, which Monahan (1986) termed the "95% fixation", and the shortcomings of this approach are investigated. An appropriate way forward is proposed.

## Ground movements

The occurrence of problems and failures on filled ground emphasises the importance of developing an adequate understanding of the behaviour of fills and of identifying potential hazards so that appropriate types of building development can be successfully undertaken


**Figure 2: Damage caused by collapse settlement of fill**
**(a) damaged downpipe (RIGHT)**
**(b) excessive tilt of house (ABOVE).**

(Charles, 1993). There are many potential causes of damaging ground movements including the following:

- the weight of the building,
- creep due to self weight of the fill,
- dissipation of pore pressures set up during the placement of clay fills,
- changes in moisture content of shrinkable clay fills,
- collapse compression on inundation.

It is not a simple matter to relate the movements which are attributable to these various causes to the state of the fill produced by compaction.

With engineered fills, the major problem is usually associated with settlement due to effects other than the weight of the building. The provision of an adequate bearing capacity is therefore not sufficient to ensure that the fill will support the building without the occurrence of damaging ground movements. Self-weight settlement is usually small for well compacted granular fills such as rockfills and most of it takes place during or shortly after fill placement. Pore pressures set up during the placement of clay fills can take years to dissipate and settlement due to primary consolidation of the fill may continue after construction of the buildings; this will be followed by secondary consolidation or creep. The weight of the fill may also cause significant settlement of the natural strata underlying the fill, an aspect that must be carefully considered.

Collapse compression on inundation often represents the most serious hazard for buildings founded on fill (Charles and Watts, 1996 & 1997). Mechanisms which can cause collapse compression in a fill include the following; weakening of interparticle bonds, softening of aggregations of particles in fine-grained fills, and weakening of particles in coarse-grained fills. Settlement of the ground due to reduction in volume of the fill occurs during this process without any change in applied total stress. Inundation may be due to a rising ground water level or downward infiltration of surface water. As it is differential settlement rather than total settlement that damages buildings, local collapse compression from a surface source of water is particularly hazardous. **Figure 2** shows damage to new houses associated with large ground movements caused by collapse settlement of fill. Poorly compacted or excessively dry fill is always likely to be vulnerable to collapse settlement on inundation and an important objective of the specification and control procedures adopted for an engineered fill will be to eliminate, or at least minimise, this type of volume change within the fill during and subsequent to building on the fill.

## Fundamentals of soil compaction

Modern procedures for the placement and compaction of fill were introduced by RR Proctor in 1933 in a series of four articles published in *Engineering News-Record* in 1933. Essentially Proctor was concerned to develop an improved procedure for the control of earthworks by simple laboratory and field tests. For more specialised soil mechanics knowledge he referred his readers to a paper published in Engineering News-Record by Terzaghi (1925). Proctor's work was associated with the construction of earthfill dams and he concluded that:

"... it is possible to compact a soil so firm and hard as to appear entirely suitable for a dam and for this same soil to become very soft and unstable when percolating water saturates it".

Thus the principal objective of Proctor was to find a method for determining and limiting collapse compression, or softening as he described it, which could occur when the earthfill was saturated with water.

BS 1377:Part 4:1990 includes several laboratory compaction test procedures. Clause 3.3 describes a test using a 2.5 kg rammer and clause 3.5 describes a test using a 4.5 kg rammer. The former test is a metricated version of the standard Proctor compaction test with a total energy input of 596 kJ/m$^3$. The latter test is a metricated version of the modified Proctor compaction test with an energy input of 2682 kJ/m$^3$. BS 1377:Part 1:1990 defines relative compaction as the percentage ratio of the dry density of the soil to the maximum compacted dry density of a soil when a specified amount of compaction is used. When quoting a value of relative compaction, the type of compaction must be specified. This is usually, although not always, the standard Proctor compaction test.

Laboratory compaction test results are plotted on a graph of dry density versus moisture content. This is a simple and useful way of representing the condition of a partially saturated fill. **Figure 3** shows results obtained by Proctor (1948a) for a clay fill using different compactive efforts. The basic laboratory testing carried out by Proctor demonstrated some fundamental features of the compaction of clay soils.

- The density to which a particular compactive effort will bring a clay fill depends on the moisture content of the fill.
- For a given compactive effort there is a maximum dry density which is achieved at the optimum moisture content. The expressions "maximum dry density" and "optimum moisture content" refer to a specified compaction procedure and can be misleading if taken out of the context of that procedure.
- At a moisture content dry of optimum, the specified compaction procedure will result in a fill with large air voids.
- At a moisture content significantly wet of optimum moisture content, the specified compaction procedure will produce a fill with a min-

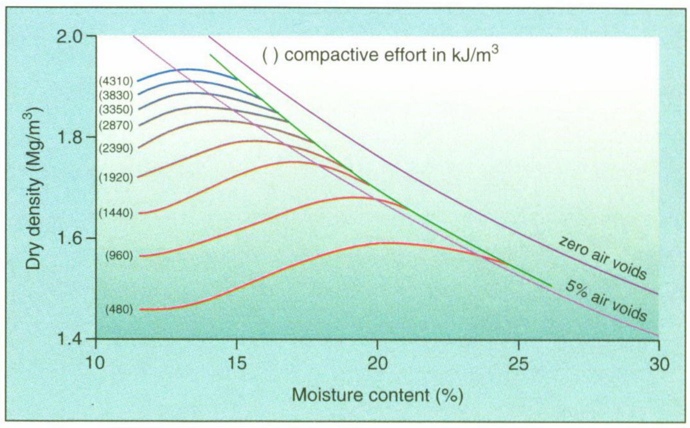


**Figure 3: Clay fill compacted using various compactive efforts (after Proctor, 1948a)**

**Figure 4: An engineered mudstone fill**
**TOP: (a) watering the fill**
**ABOVE: (b) compacting the fill.**

imum air voids, typically between 2% and 4%.

These fundamental factors demonstrate that the control of moisture content is crucial for field control of compaction. **Figure 4** shows a mudstone fill being wetted prior to compaction. Holtz (1948) proposed two moisture content limits for clay fills as it was recognised that:

- a moisture content that was too high could lead to excessive construction pore pressures,
- a moisture content that was too low could lead to excessive settlement of the fill when the fill became saturated.

With respect to fills for building developments, the upper limit for placement moisture content corresponds to a fill where the bearing capacity is too low and the settlement produced by the weight of the building is too great.

The lower placement moisture content for a clay fill was defined by Holtz as the moisture content at which saturation would have no effect on consolidation. However, collapse compression on saturation is related not only to the moisture content, but also the dry density or percentage air voids. Proctor (1948a) showed that the energy required to reduce the air voids in the fill to a minimum was related to the undrained shear strength of the soil and that the subsequent compression behaviour was also related to the strength after compaction.

## Fill specifications and the "95% fixation"

Earthworks specifications can be of three basic types:

- method specifications in which the procedure for the placement and compaction of the fill is specified,
- end-product specifications in which some properties of the fill as placed and compacted are specified,
- performance specifications in which some aspect of the behaviour of the completed fill is specified.

The merits of the different approaches have been reviewed by Trenter and Charles (1996) and for relatively small volumes of fill (< 50,000m$^3$) for residential and commercial developments it was concluded that an end-product specification was preferable. This raises the question of how the end-product is to be specified. One commonly used approach has been to require a field density that is some proportion (usually 95%) of the maximum dry density in the standard laboratory Proctor compaction test. This is commonly termed 95% relative compaction.

The use of 95% relative compaction as the criterion for acceptability in earthworks specifications has been challenged:

"Since the reasonable but otherwise arbitrary choice of 95% Proctor densities as the target value for fill control work of the 1920s was made, there has developed a fixation on the part of specification writers to require this percentage compaction, irrespective of loadings, fill thickness, or other factors that should logically influence compaction requirements. There are a number of causes for this practice: a reluctance to specify anything different than is "customary", nonspecialists writing compaction specifications, and the fact that there is no widely accepted rational method for specifying percentage compaction appropriate for specific conditions." (Monahan, 1986)

This complaint in the entertaining and instructive book

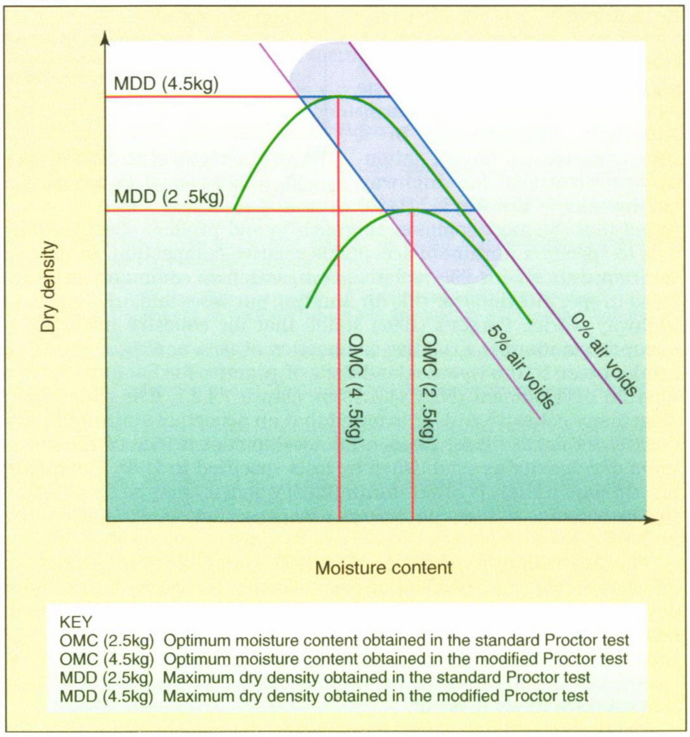


**Figure 5: Proposed basis for end-product specification (after Trenter and Charles, 1996).**

"Construction of and on compacted fills" was not original as Proctor had criticised this type of development in 1948:

"However, published literature regarding the use of these methods by other organizations describes procedures that fall short of the objective intended in 1933, particularly in the use of 90 and 95% of the many "optima" soil dry weights secured by various combinations of a 12 or 18 inch drop of 5-1/2 or 10 lb tampers on one or two inch soil layers in compaction cylinders of 1/20 or 1/30 cu ft capacity, rather than the use of the penetration resistance of soils when saturated ...." Proctor (1948b)

The continuing use of the 95% relative compaction criterion in the United States is confirmed in a recent specialist text book on "Ground control and improvement" (Xanthakos et al, 1994):

"Commonly specifications require that dry densities be obtained in the field that are at least equal to 95 percent of maximum dry density determined on the basis of laboratory tests. The type of test used must be specified .."

However, elsewhere in this book a warning note is sounded: "The degree of compaction is normally specified in terms of a minimum percentage of the maximum dry density obtained from laboratory testing of the fill soils. For most projects, 90% to 95% of the maximum density is adequate except under pavements, slabs, footings, and other structural elements. In these cases, 100% maximum dry density may be required."

Although the foregoing quotations originate from the USA, it should not be assumed that the "95% fixation" is a peculiarly American idiosyncracy. In a review of many different national specifications for highway earthworks, Reichert (1990) found that the most common approach in end product specifications was to specify a minimum acceptable relative compaction. In the UK the requirement for 95% relative compaction is commonly encountered in specifications for fills for building purposes and, in relation to highway works, Parsons (1992) stated that for cohesive materials a common standard is a relative compaction of 90% or 95% of the 2.5kg rammer test. In the New Zealand Code of practice for Earthfill for residential development (NZS 4431:1989), clause 7.4.2.1, it is stated that: "For many cohesive soils it is found that an acceptable minimum dry density for earth fill for residential development is 95% of the maximum dry density as established by tests specified in 11.8*. For highly plastic clays a slightly lower minimum dry density may be specified by the inspecting engineer to reduce post-construction swelling of the bulk fill."

The Australian Standard AS 3798-1990, Guidelines on earthworks for commercial and residential developments, proposes a minimum dry density ratio of 95% for cohesive soils for residential developments where dry density ratio refers to standard compaction energy input. A footnote warns that a ratio of 98% or higher may need to be considered if collapse on saturation, excessive settlement, or dispersive soils are likely to occur.

Trenter and Charles (1996) have produced a model specification for engineered fills for building purposes. For projects involving relatively small volumes of fill (<50,000m³), they have proposed the use of an end-product specification in terms of air voids being 5% or smaller as illustrated in **Figure 5**.

*Clause 11.8 refers to the standard compaction test.

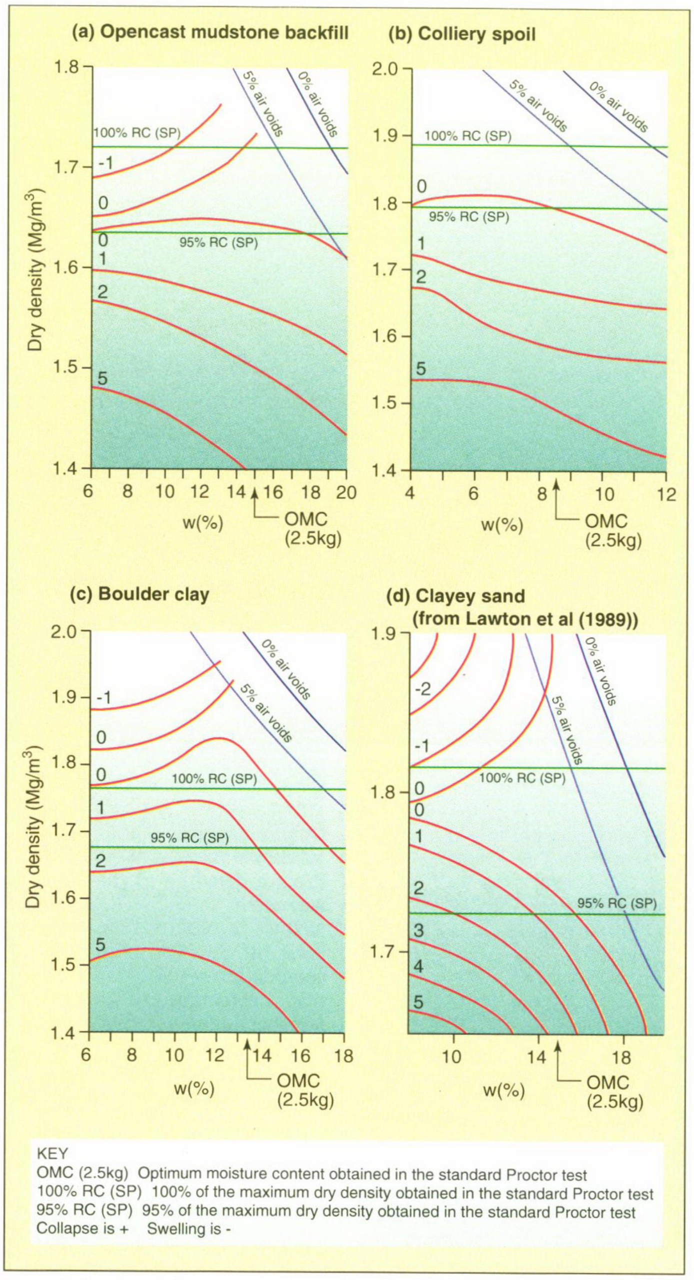


**Figure 6: Contours of percentage volume change on submergence [$\sigma_v$ = 30kPa for (a), (b) and (c), $\sigma_v$ = 400kPa for (d)]**

## Collapse compression and the "95% fixation"

In order to make a full evaluation of the appropriateness of 95% relative compaction as the sole requirement for the compaction of fills, it would be necessary to determine the implications of such a specification for the various types of ground movement that can occur across a comprehensive selection of fill types and in relation to a wide spectrum of types of construction. This is beyond the scope of the present work. However, collapse compression has been identified as the principal hazard for fill which will be built on and it has been possible to make a preliminary assessment of the compaction required to ensure that fill has zero, or minimal, collapse potential for a few selected types of fill.

There has been earlier work in this area. Walker and Holtz (1951) presented data for a silty clay showing the way in which collapse compression reduced as the air voids after compaction reduced. Cox (1978) carried out test on Keuper Marl. Clayton and Simons (1980) reported results from tests on a compacted hoggin fill. Lawton et al (1989) have provided contours of collapse compression for a soil that was classified as a clayey sand in the Unified Soil Classification System.

A small preliminary laboratory test programme has been carried out at BRE on three fill materials; a granular colliery spoil, an opencast mining mudstone and a boulder clay. Basic soil data are presented in **Table 1**. Tests have been carried out in a 150mm diameter oedometer on recompacted samples 80mm high. The samples were wetted to the appropriate moisture content, compacted in the oedometer ring to the required density, loaded to 30kPa and then submerged. Generally there was a rapid response to submergence and the resulting movement was measured until the rate of movement had decreased to below 0.001mm/minute. Some denser samples were left for several days to allow the full swelling to take place. Contours of percentage volume change on submergence are plotted for the three fills in Figure 6. The maximum dry density obtained in a standard Proctor compaction test and 95% of this dry density are indicated for each fill. The results for a clayey sand fill at a vertical stress of 400kPa (Lawton et al, 1989) are also included in **Figure 6**.

The BRE results plotted in Figure 6 all refer to submergence at a low applied vertical stress. The value of 30kPa was chosen in order to correspond to the fill as tested in the BRE test pit facility (Charles and Watts, 1996). Clearly the results are stress dependent and both Cox (1978) and Lawton et al (1989) have provided data showing the extent of stress dependency on collapse compression contours for the soils that they tested. Tests at BRE have indicated that for many fills there is a minimum stress, often very small and typically about 10kPa, below which collapse does not occur. There is then a wide range of stress, typically from 20kPa to 400kPa, within which the stress level does not have too great an effect on collapse potential. At very high stresses collapse potential is suppressed. The results obtained with collapse at

**Table 1: Fill properties.**

| Fill type | Plasticity indices | | Fines fraction | Particle density | Standard Proctor[1] | | Modified Proctor[1] | |
|---|---|---|---|---|---|---|---|---|
| | $w_p$ | $w_L$ | % < 0.06 mm | | MDD | OMC | MDD | OMC |
| Mudstone opencast backfill | 18 | 40 | 64 | 2.56 | 1.72 | 15 | 1.78 | 11 |
| Colliery spoil | - | - | 10 | 2.42 | 1.89 | 8.5 | 1.99 | 7 |
| Boulder clay | 20 | 60 | 58 | 2.71 | 1.77 | 13.5 | 1.98 | 10.5 |
| Clayey sand[2] | 15 | 34 | c35 | 2.73 | 1.82 | 15 | 2.02 | 10 |

Note 1: MDD = maximum dry density
OMC = optimum moisture content
Note 2: from Lawton et al (1989)

30kPa vertical stress will tend to under-estimate the collapse at higher stresses. Jennings and Knight (1957) described a double oedometer test procedure in which one sample is loaded at the in-situ moisture content and then inundated with the maximum load applied to the sample, while the other sample is inundated prior to loading. This testing procedure can give a measure of collapse potential over a wide range of stress and some double oedometer tests have indicated that collapse compression for the fills in the BRE test programme would have been somewhat greater if the samples had been submerged at stresses in the range of 50kPa to 400kPa.

The results of the tests suggest that 95% relative compaction based on the standard Proctor compaction test might largely eliminate collapse potential with some fills but with others there could be a collapse potential of as much as 2% where the fill is compacted dry of optimum moisture content. Thus, on its own, a 95% relative compaction criterion is not an adequate compaction requirement. It might be satisfactory if it was linked to a criterion of air voids of 5% or smaller or, possibly for some fills, to a criterion of a moisture content greater than standard Proctor optimum.

## Conclusions

Filled ground can present particular hazards for buildings constructed upon it due to settlement or, occasionally, due to heave. Specifications for engineered fills for residential and commercial developments have often been derived from highway earthworks specifications and these are not necessarily adequate for fills on which buildings will be founded. The importance of moisture content control has sometimes been ignored.

The appropriateness of any specification needs to be examined in terms of the ground movements which may occur subsequent to building on the fill. Collapse compression is the major hazard for buildings on fill and some tentative conclusions relating collapse compression to the common specification requirement for a minimum of 95% relative compaction based on the standard Proctor test have been reached from the limited BRE laboratory test programme.

- For a granular soil it should be possible to specify a relative compaction above which there should be no ground movements on inundation, although 95% of the maximum dry density in the standard Proctor compaction may not be an adequate standard.
- For a cohesive soil it is not possible to specify a relative compaction above which there will be no ground movements on inundation, as heave will occur on inundation of soils with a very high relative compaction.
- For most of the fills, collapse compression occurred at some moisture contents even though a relative compaction of 95% had been achieved. Although this level of compaction might largely eliminate collapse potential for some fills, with others there could be a collapse potential of as much as 2% where the fill was compacted dry of optimum moisture content.

Thus, for many fills, specifications which rely solely on a requirement of at least 95% of the maximum dry density obtained in the standard Proctor compaction test will not eliminate collapse potential, and consequently this does not constitute an adequate compaction specification. Trenter and Charles (1996) have proposed the use of an end-product specification in terms of air voids being 5% or smaller and this would seem to form the simplest basis for specifying a fill with no collapse potential.

The laboratory test results suggest that this criterion is likely to be satisfactory, although there could be some heave with densities greater than the maximum dry density obtained with modified Proctor compaction. However, reliable field measurement of percentage air voids via density and moisture content determination is time consuming and difficulties are sometimes encountered.

The current preliminary investigation has several shortcomings:

- only those ground movements which are due to collapse compression have been examined,
- only a restricted number of fills have been tested,
- only small scale oedometer tests have been undertaken.

There is a need for further work to link ground movements which can be expected subsequent to building with the as compacted state of the fill for a wider range of fills and due to all likely causes. Laboratory test results need to be calibrated against measured field performance.

## Acknowledgements

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