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SHALLOW FOUNDATION PROBLEMS AND GROUND CONDITIONS IN TORBAY

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Problems with shallow foundations are unusually common in Torbay. Subsidence cases run at perhaps twice the rate (per head of population) of other urban areas in South West England. The distribution of cases in Torbay is controlled by the underlying geology. Dramatic problems are associated with solution features in the Devonian limestones, but although these can be severe, they are not common, and the firm silty clays developed on the limestones do not normally give rise to problems. Ground conditions on the Devonian slates, sandstones and igneous rocks are generally good, although movement due to shrink-swell of residual highly plastic silty clay soils is known locally. Problems associated with soils developed on Permian breccias are both very common and often severe: these are sometimes associated with loess horizons within the soil profile. Amongst the breccias, problems are much more common on the Oddicombe Breccia than on the Watcombe Breccia. The worst ground conditions occur where thick colluvial deposits are developed on lower hillslopes on the Oddicombe Breccia; the colluvial soils are unconsolidated sandy silts which are very susceptible to loss of strength on wetting.

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GEOLOGY

The urban areas of Torbay are underlain by complexly folded and faulted rocks of Devonian age, overlain unconformably by younger, probably Permian, strata. The Devonian rocks include limestones, various argillaceous and arenaceous sediments, and igneous rocks which are mostly volcanic but also include small high-level intrusions. All the Devonian rocks have been subjected to very low grade metamorphism, and the originally clay-rich rocks contain illite +1- chlorite +1- kaolinite (Warr, 1995; Cattell, 1998). In this contribution, the Devonian rocks are divided into 2 groups, simply on the basis of the shallow ground conditions that develop on them. A similar subdivision was made by Doornkamp *et al.* (1988). The limestones form one group, because of the solution features they commonly exhibit. All other Devonian rock types are grouped together and referred to as `slates and tuffs', even though some of the sediments are quite arenaceous and some of the igneous rocks are lavas or high-level intrusions. The probable Permian strata consist of red breccias and sandstones. These are divided into 2 stratigraphic units, the Watcombe Breccia and Oddicombe Breccia (Doornkamp *et al*., 1988). The older Watcombe Breccia is characterised by the presence of many clasts of slate, whilst the Oddicombe Breccia is characterised by abundant clasts of grey limestone.

SUBSIDENCE

The foundation problems described here are those of subsidence, and some explanation of the term is required. The term is used here in the way it is generally used in the insurance industry, since most of the sites from which the geotechnical data were obtained were the subjects of insurance claims for subsidence. Damage is covered by insurance if it has been caused by an event which occurred during the currency of the insurance policy. Applying this to damage due to foundation movement, it means that foundation movements due to originally poor foundations or originally poor ground should not be covered, but damage due to foundation movement caused by an event after construction may be covered. A distinction is therefore made between settlement and subsidence.

Settlement is foundation movement caused by the response of the soils to the newly imposed load of the building. It starts immediately upon construction, although it may continue at a gradually decreasing rate for months or even years, depending on the soils present. Both the extent and timing of the settlement should be predictable if the soil parameters and loads are known.

In contrast, in Torbay subsidence starts some time after construction, and is caused by a change in ground conditions whilst the load remains constant. The timing and extent of subsidence movement is not generally predictable. Almost all subsidence cases in Torbay are caused by a change in the moisture content in the soil. This can either be a drying out of the soil and consequent shrinkage, leading to at least partially reversible subsidence, or wetting and softening of the soil leading to shear failure or compression, which is irreversible. The likelihood of either or both mechanisms operating depends on the nature of the soils.

Often subsidence occurs where foundations are laid on fill. Except for deliberately engineered examples, fills are loose and are usually very susceptible to compaction on wetting. The distribution of these man-made soils is generally not predictable in the study area, and subsidence caused by such materials is almost randomly distributed over the urban areas. This study deals only with cases where subsidence occurs on natural ground.

When the effect of fills is removed, the very strong correspondence of subsidence with underlying bedrock is clear (Figure 1). The Oddicombe Breccia underlies less than a third of the built-up area of Torbay, yet accounts for over 85% of the cases where subsidence was severe enough for underpinning to be required. This not only shows that the risks of subsidence on the Oddicombe Breccia are very high, but also shows the more general point that the shallow soils in the area reflect very strongly the underlying bedrock. In the following sections, the ground conditions developed on the major bedrock types are described.

SOILS ON LIMESTONE

Limestones underlie parts of the centre and east of Torquay, much of southern Paignton, and virtually all of Brixham. Neither the Geological Survey map (soon to be superseded) nor the applied geology maps (Doornkamp *et al*., 1988) make any subdivision of the limestones. It is therefore not possible to relate any variation in shallow ground conditions to variation in the limestone bedrock, although this may become possible in the future, when the new Geological Survey sheet is published.

Soils developed on the limestones are most commonly red firm silty clays of medium plasticity (Figures 2a and 3). Soft dark brown manganese-rich soils, or umbers, are locally developed, particularly in

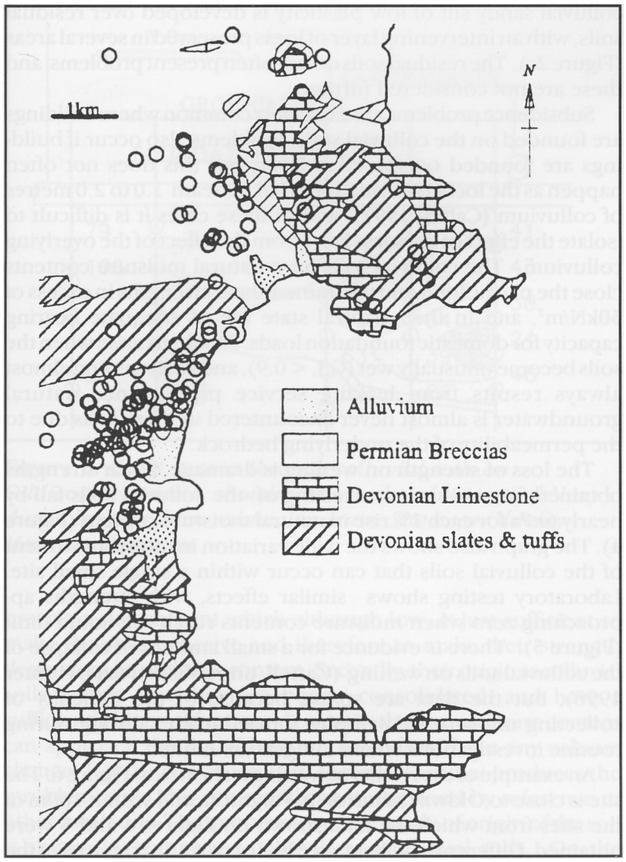

Figure 1. *Geology of Torbay, showing sites of subsidence investigated by the author, excluding sites where damage was trivial, and sites where problems were caused by made ground, rather than the natural soils.*

the Galmpton area. The limestones often have a karstic surface, so the soil thickness is highly variable and unpredictable. Foundation problems caused by shallow ground conditions on the limestones are uncommon. The soils are generally firm or stiff and of adequate bearing capacity, and seem to be too impermeable to be affected by leaks from service pipes. Their plasticity is too low, and the soils are usually too thin, for seasonal shrink-swell movements to be significant except where large trees are growing very close to a building. Minor problems do occur because of differential foundation movement over a karstic surface, where part of a building is founded on rock on a high on the surface, and part on a metre or so of soil over a bedrock low. However, such examples are rare. Although problems caused by umber (which readily compresses on wetting) are possible, none are known where bedrock is at shallow depth.

Problems caused by deep solution features in limestone are beyond the scope of this contribution. However it should be noted that subsidence problems do occur in Torbay from this cause. These are not common, but can be dramatic and expensive to deal with, since the solution features can be tens of metres deep. Cases are known from the south Paignton and Galmpton areas, and the solution features seem more common where the limestone is faulted and/or in contact with slates or tuffs. As with many other foundation problems, subsidence problems from this cause usually stem from a leaking service pipe or a soakaway, the infill of the solution feature remaining stable under natural conditions and only failing when it becomes saturated.

SOILS ON SLATES AND TUFFS

A rather heterogeneous group of rocks are grouped together into this category, and consequently the soils derived from them are

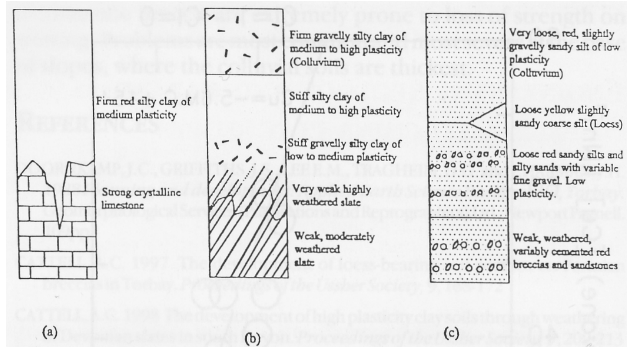

Figure 2. *Typical soils developed on the main bedrock types in Torbay. (a) Devonian Limestone, (b) Devonian Slates and tuffs (profile based on Middle Devonian Slate), (c) Permian Breccia (profile based on Oddicombe Breccia). Vertical thickness of sections is 2 metres, but all show considerable variation.*

are variable (Figure 3). Nevertheless, the ground conditions developed on them do form a coherent group. Although there is much variation, there is nearly as much variation in conditions on individual rock types as there is variation between different rock types. The variations that can be related to bedrock are noted in the following descriptions.

The soils are firm and stiff brown silty clays, with some redder soils at sites close to the pre-Permian unconformity. The development of soils depends on the topography of the site. Relatively thin soils are developed on flatter upland sites, and here there is often preserved a gradation from silty clay, down through increasingly gravelly soils into weathered bedrock, and in excavations a 'ghost' cleavage can be traced up from bedrock into the soil profile - clearly showing the residual origin of these soils (Figure 2b). The highest plasticity soils occur in this situation, and usually on slates mapped as Middle Devonian in age (Cattell, 1998). On sloping sites there is usually evidence for downslope soil movement, leading to more homogeneous moderately plastic silty clays with significant gravel contents.

Foundation problems on the slates and tuffs are not common. Moisture contents are usually just below the plastic limit (mean C.I. = 1.32) and are never raised far above the plastic limit (minimum C.I. = 0.75), and shear strengths do not fall significantly below 50kN/m^2, which is sufficient for normal domestic foundation loadings. Consequently, subsidence problems caused by leaking services are not significant on the slates and tuffs. Problems caused by shrink-swell movements of the more plastic clay soils are known

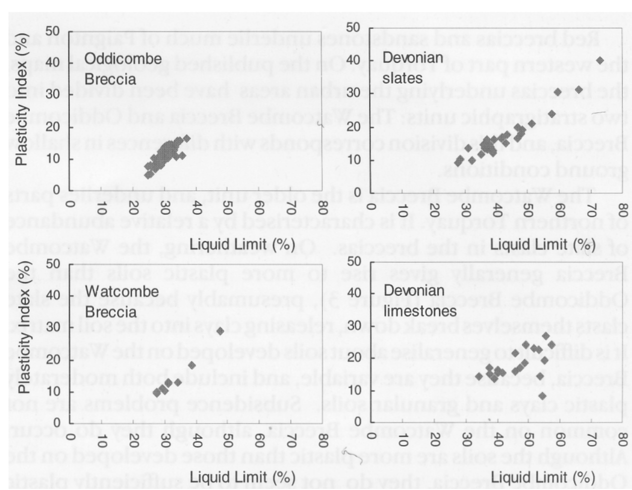

Figure 3. *Plasticity data for soils developed on various bedrock types in Torbay. The plasticity of the soils reflects mainly the clay content and mineralogy of the underlying bedrock.*

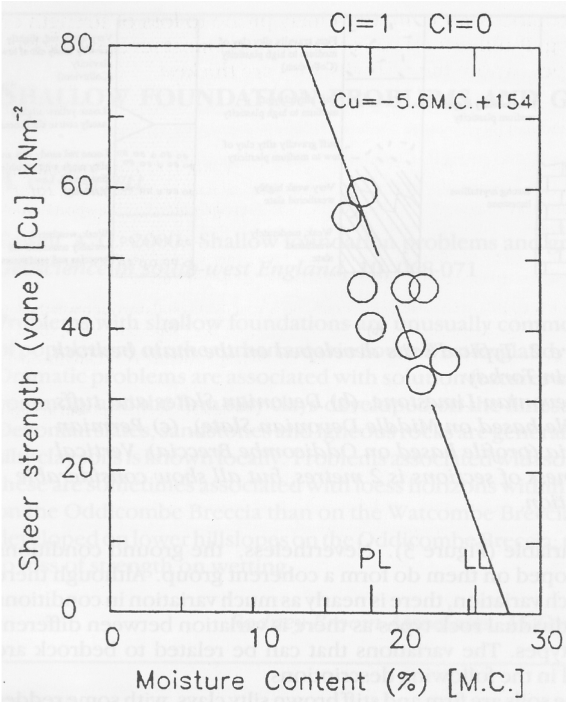

Figure 4. *Effect of moisture content on shear strength measured by in-situ vane testing. Best fit line shown for reference (r = 0.50). Colluvial soil on Oddicombe Breccia, near Oldway Mansion, Paignton.*

from Torquay, but are not common, and few occurred even in the hot dry summer of 1996. Although cases usually occur on high plasticity clays, one example of significant seasonal movement (crack opening by > 2mm in summer 1995) occurred on a thin low-plasticity soil (P.I. = 10.0%) over weathered slate of the Staddon Grits in the Lincombe area of Torquay. In this instance there were several mature trees in close proximity to the building, and the desiccation caused by these in the less extreme summer of 1995 was sufficient to shrink even such low plasticity materials enough to damage the building. (The affected corner had been underpinned by the hot dry summer of 1996.) However, the examples' are the exception rather than the rule, and subsidence problems related to shrink-swell of clay soils is very uncommon in Torbay.

SOILS ON PERMIAN BRECCIAS

Red breccias and sandstones underlie much of Paignton and the western part of Torquay. On the published geological maps, the breccias underlying the urban areas have been divided into two stratigraphic units: The Watcombe Breccia and Oddicombe Breccia, and this division corresponds with diferences in shallow ground conditions.

The Watcombe Breccia is the older unit, and underlies parts of northern Torquay. It is characterised by a relative abundance of slate clasts in the breccias. On weathering, the Watcombe Breccia generally gives rise to more plastic soils than the Oddicombe Breccia (Figure 3), presumably because the slate clasts themselves break down, releasing clays into the soil matrix. It is difficult to generalise about soils developed on the Watcombe Breccia, because they are variable, and include both moderately plastic clays and granular soils. Subsidence problems are not common on the Watcombe Breccia, although they do occur. Although the soils are more plastic than those developed on the Oddicombe Breccia, they do not seem to be sufficiently plastic' for shrink-swell problems to develop, and these have not been encountered.

The soils developed on the Oddicombe Breccia have been described previously (Cattell, 1997). In summary, a layer of colluvial sandy silt of low plasticity is developed over residual soils, with an intervening layer of loess preserved in several areas (Figure 2c). The residual soils do not often present problems, and these are not considered further.

Subsidence problems are extremely common where buildings are founded on the colluvial soils. Problems also occur if buildings are founded on the loess layer, but this does not often happen as the loess is normally buried beneath 1.0 to 2.0 metres of colluvium (Cattell 1997), and in these cases it is difficult to isolate the effect of the loess layer from the effect of the overlying colluvium. The colluvial soils have natural moisture contents close the plastic limit and undrained shear strengths in excess of 50kN/m^2, and in their natural state are of adequate bearing capacity for domestic foundation loads. Problems arise when the soils become unusually wet (C.I. < 0.9), and such wetting almost always results from leaking service pipes, since natural groundwater is almost never encountered in these soils due to the permeability of the underlying bedrock.

The loss of strength on wetting is dramatic. Shear strengths obtained from in-situ vane testing of the colluvial soils fall by nearly 6kPa for each 1% rise in natural moisture content (Figure 4). The graph also shows the wide variation in moisture content of the colluvial soils that can occur within a single small site. Laboratory testing shows similar effects, with strengths approaching zero when moisture contents reach the liquid limit (Figure 5). There is evidence for a small amount of collapse of the colluvial soils on wetting (Cattell, unpublished data, Hunter 1998), but the data are sparse because of the difficulty of collecting undisturbed samples for oedometer testing during routine investigations where budgets are limited.

An example of the results of wetting is shown on Figure 6. The site is close to Oldway Mansion in Paignton, and within 100m of the sites from which the data shown on Figures 4 and 5 were obtained. Differential subsidence had occurred in the area of the building next to a rainwater drain, which was found to leak. A traverse of auger holes, from the stable corner of the building to the leaking drain, showed large and rapid changes in shear strength caused by the variation in moisture content (moisture contents were not measured, but can be estimated from Figure 4 as ranging from c.17% to 25%). The very large variations in shear strength over relatively short vertical and horizontal distances are common in these soils.

The susceptibility of the soils to loss of strength on wetting is clearly unusually high. This seems to stem from two aspects of their origin. Firstly, they have inherited from the underlying breccia a clay

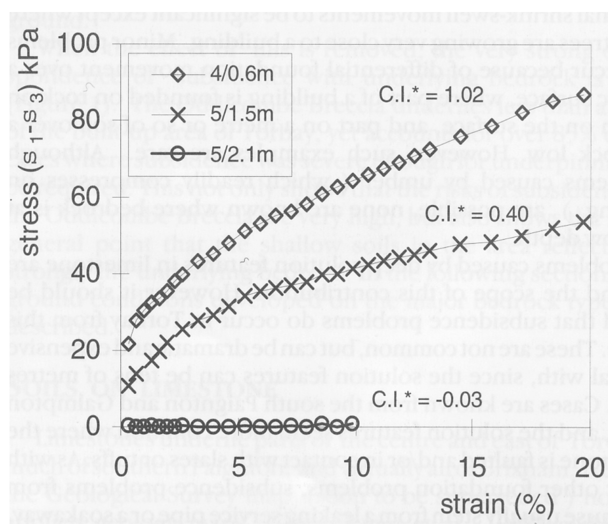

Figure 5. *Quick undrained triaxial test results on sandy silts at differing natural moisture contents from a site on the Oddicombe Breccia near Olway Mansion, Paignton. Tests according to BS1377 (1990), tests terminated at 20% strain. CI.* =Consistency Index corrected for coarse fraction (when natural moisture content is at plastic limit, C.I. =1.0, when natural moisture is at liquid limit, CI. =0.0)*

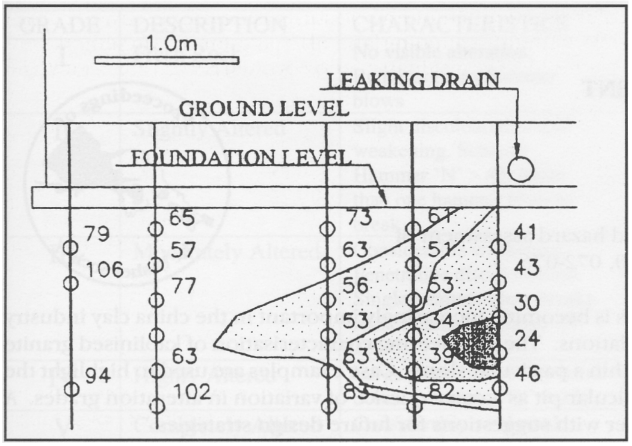

Figure 6. *Cross section through colluvial soils on Oddicombe Breccia, showing fall in shear^2 strength (kN.m) due to leakage from rainwater drain. Site near Oldway Mansion, Paignton.*

content which although low, is just sufficient to make the soils cohesive and therefore to make their strength dependent on moisture content. Secondly, their origin as colluvial soils means that they are poorly consolidated, and have a sufficiently high void ratio and porosity that the moisture content can approach the liquid limit of the soils without any volume change. It is the combination of these factors that produces the `problem' soil. This can readily be understood by reference to other local soils. The importance of the mode of origin of the soil is shown by comparing colluvial and residual soils. On the Oddicombe Breccia, the residual soils and the colluvium have virtually identical plasticity and grain size distributions. The residual soils are not significantly affected by wetting because they have a more compact structure - their dense grain structure is inherited from the Permian sediments which have been compacted by long-term burial, even though they may have lost some soluble components through weathering.

The importance of the source material is shown by comparing colluvial soils on the Oddicombe Breccia with those developed on other bedrock. Colluvial soils are developed on the slates and tuffs, but these soils are more clay-rich than those on the Oddicombe Breccia, and moisture contents are only rarely much above the plastic limit.

The colluvial origin of the 'problem' soils strongly controls the distribution of subsidence problems over the outcrop area of the Oddicombe Breccia in Torbay. Since the soils form by downslope movements it is not surprising that they are thickest (usually > 2m) at the bottom of slopes, and thin or absent on upper slopes and ridges. The result is that subsidence cases are concentrated on the dry valley floors (21%) and lower slopes (53%), but rare on the upper slopes (9%) and absent on the ridges. The remainder of cases (17%) occur on a low-lying area of subdued topography, inland of the alluvial coastal plain at Paignton, where colluvial material has moved down from steeper slopes inland.

CONCLUSIONS

The frequency of subsidence problems in shallowly founded buildings correlates strongly with bedrock in Torbay, the likelihood of problems on Oddicombe Breccia being roughly twenty times the likelihood on other rock types.

On Devonian slates and tuffs, the most common problem is seasonal movements caused by shrink-swell of silty clay residual soils, but such cases are uncommon.

On limestones, problems are caused by karstic features: the problems can be severe, but are rare.

On the Oddicombe Breccia, problems are caused by leaking services wetting the soils. Colluvial soils developed on the Oddicombe Breccia are extremely prone to loss of strength on wetting. Problems are most common and most severe at the base of slopes, where the colluvial soils are thickest.

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