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CALIFORNIA HOUSING DAMAGE RELATED TO EXPANSIVE SOILS

By Richard L. Meehan[1] and Lawrence B. Karp,[2] Members, ASCE

ABSTRACT: Differential movements of foundations on expansive soils have caused damage to thousands of homes in California. Building damages or just out-of-level floors have resulted in widespread claims and repair expenses. This paper discusses historical and environmental conditions which have led to these problems in California. It describes the current state-of-the-art in foundation design and construction methods used to minimize movements, characterizes out-of-level conditions, and recommends tolerances to assist in evaluating the performance of residential structures. The authors conclude with a summary of considerations and comments on how some of the barriers to upgrading professional engineering practice relative to expansive soils might be overcome.

INTRODUCTION

Expansive soil/rock damage to housing developments has been a problem that has become widely identified in California since the introduction of mass-marketed housing after World War II. Recognition of the problem by designers, developers, and building officials is leading to some mitigation of this problem, although increased development costs coupled with the current (1990s) trend toward "affordability" through construction "economies" may exacerbate it. Recent experience shows that construction of some foundation systems, such as the use of posttensioned slabs-on-ground, originally developed to solve problems, can result in new and costly problems. In any case, the response of the building industry to utilize engineering and construction technology is slow and fragmented.

The writers have provided technical consultation involving problems arising principally from expansive soil damage to a variety of buildings and housing tracts in California. Investigations have varied from brief visual inspections to detailed autopsies involving dismantling of the affected houses. Projects investigated vary from tracts of several hundred moderate cost houses, built between the 1960s and the 1980s in outlying suburbs, to expensive custom homes in the urban areas. The usual case is one where marginally effective foundation designs have led to differential foundation movements ranging from 25–75 or 100 mm (1–3 or 4 in.). Both cause and significance of this level of performance is often disputed.

In the case of a typical single family house that has moved several inches one may hear at one extreme that the damage is insignificant and that the cause is some minor combination of normal wear and tear and normal timber shrinkage, combined with inevitable minor foundation settlement. At the other extreme one may hear (for the same house) that the damage is intolerable and will worsen, that it makes the property "unsalable," or even that the structural safety of the building has been compromised.

Over the past few years there has been a desirable convergence of profes-

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[1] Consulting Geotech. Engr., 701 Welch Rd., Palo Alto, CA 94304.

[2] Consulting Geotech. Engr., 100 Tres Mesas, Orinda, CA 94563.

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sional engineering opinion on these matters. Accumulated experience now allows for some general guidelines aimed at establishing standards of acceptable performance, as suggested herein.

ENVIRONMENTAL CONDITIONS

Geology of Expansive Claystones

Expansive soils exist in California because of the general geologic activity that is associated with the state's location on the edge of the Pacific Rim. Disturbances of the geologic mantle gave rise to volcanic activity in the central part of California during Tertiary times, some 35,000,000 years ago. Volcanos produced ash that fell to the ground or into water (e.g. tuff) and subsequently weathered to montmorillonite-rich clay. (Much the same process occurred during the recent eruption of Mount St. Helens.) Over time, the result in California has been an accumulation of young sedimentary deposits possessing little secondary cementation or lithification, i.e. so-called compaction claystones, variously interbedded with sandstones and siltstones. Continuing tectonic disturbance of these Tertiary-age beds resulted in their being folded and faulted, forming the hills which range up to a thousand or so feet above sea level along California's coastal regions. The folding process has in some areas produced beds dipping at relatively uniform angles as in the notorious Orinda Formation east of Berkeley or elsewhere mixed in a more chaotic melange as in parts of the Butano Formation on the San Francisco Peninsula.

The more clay-rich members of these formations exist as discrete beds usually several feet thick and seldom visible except where exposed on cliffs or by excavations. When wet, these "rocks" quickly revert to a sticky clay. Swelling occurs when they are exposed to moisture or are unloaded from overburden. They typically give rise to other types of instability, including landsliding, soil creep, or earth flows.

Natural water content of these claystones is typically in the 20–25% range, with plasticity indices (PIs) usually varying between 35 and 50. Volumetric shrinkage proceeds at about 2% for each 1% change in water content, and with exposure to drying, shrinkage proceeds until the shrinkage limit, typically 15%, is reached. This significant shrink potential, present even in rock-like claystones, is itself a major potential source of damage. For example, 15% volumetric shrinkage of only 0.6 m (2 ft) of supporting rock can lead to severe damage to most houses. Engineering attempts to achieve immobility by strengthening foundations may fail because of the large forces and often unpredictable directions involved. Access to moisture produces swell pressures of about 150–500 kPa (3,000–10,000 psf); swell index is 0.03 to 0.08 per log cycle of load.

These troublesome claystones, typically of Tertiary geologic origin, can usually be identified from geologic maps. Other older clayey rocks (mudstones) underline much of the coastal ranges, e.g. the Franciscan Formation, but these older, metamorphosed clays are less plastic and do not give rise to such severe problems as the younger claystones.

Although expansive Tertiary claystones do give rise to serious problems when encountered in hillside land grading (Meehan et al. 1975), the majority of mapped expansive soils are located down slope from expansive claystones. These soils exist as colluvium or, in larger valleys, as alluvial soils selectively deposited in lowland, poorly drained areas of the valley floor. However, the presence of Tertiary claystones in the surrounding hills is a strong indicator of the presence of expansive soils in the valleys below.

Diagnosing Expansive Soils

In the early 1970s, the Federal Housing Administration (FHA) (1973), San Francisco Insuring Office, classified the degree of expansiveness of soils according to their plasticity indices and liquid limits shown in Table 1.

The original FHA chart classified soil groups A, B, C, and D. To this the writers have added a class E, representative of the claystone bedrock found in hillside areas as discussed in the previous section. Swell indices $(C_s/1+e)$ for soils D and claystones E are about 0.03 and 0.08, respectively. For cyclic soil moisture changes common in California, houses built on D soils with conventional foundations are likely to suffer 50–75 mm (2–3 in.) differential movements over the years. Conventionally designed shallow foundations usually shift 150–300 mm (6–12 in.) in claystones that fall in the type E classification.

Although the usual practice is to classify expansive soils by their plasticity index (PI), since 1973 the *Uniform Building Code* (*UBC* 1991) has used a comparable expansion index (EI). Correlation between PI and EI parameters are summarized in Table 2.

In the absence of specific swell tests, FHA publications correlate PI to swelling pressures; PIs of 25% are indicated as inducing an uplift pressure on the order of 20,000 kPa (3,000 psf or 22 psi) or more, depending on colloidal activity (ratio of PI to clay size fraction). This agrees with the writers' local experience with expansive soils. However, type E (classified in Table 1) expansive claystones cause uplift pressures of about 479 kPa (10,000 psf) or more, depending on stress history and confinement.

Current Post-Tensioning Institute (PTI) design recommendations for PT slabs-on-ground are not primarily based on PI; the controlling design pa-

TABLE 1. FHA/HUD Classification of Expansive Soils

Soil group (1)	PI (%) (2)	LL (%) (3)	Classification (4)
A	0–6	0–25	Nonexpansive
B	6–10	25–30	Marginal
C	10–25	30–50	Moderately expansive
D	25+	50+	Highly expansive
E	50+	70+	Expansive claystone

TABLE 2. Plasticity and Expansive Indices Correlations

Soil test	Approximate Ranges				
(1)	(2)	(3)	(4)	(5)	(6)
Plasticity index	5–10%	10–15%	12–25%	20–45%	40%+
Clay content (>2 μm)	5–10%	10–15%	15–25%	25–35%	35–60%
Potential expansion (classification)	Very low	Low	Medium/ moderate	High	Very high
Expansion index	0–20	21–50	51–90	91–130	130+
Swell 2.8 kPa (60 psf) in situ	0–3%	3–5%	5–10%	10–15%	15%+
Swell 6.9 kPa (144 psf) in situ	0–2%	2–4%	4–7%	7–12%	12%+
Swell 31 kPa (650 psf) in situ	0%	0–1%	1–4%	4–6%	6%+

rameter is percent of clay fraction. For example, the PTI tables entitled "Differential Swell Occurring at the Perimeter of a Slab for a Center Lift Swelling Condition in Predominantly Montmorillonite Clay Soil" show that at a depth to constant suction = 1.5 meters (5 ft); soil suction constant = 3.2; velocity of moisture flow constant = 0.7; and edge penetration distance = 1.5 meters (5 ft), values of 42 mm (1.66 in.) differential swell for 40% clay and 69 mm (2.71 in.) for 50% clay are given (*Design* 1980). Problems with PT slabs on grade in service include the effects of poor design (which are habitually lack of stiffness and sometimes tendon looping, and seldom required strict inspection specifications), common construction defects (such as misplaced tendons and irregular slab thickness), and long-term performance flaws (including loss of prestress and corrosion).

Characteristics of Expansive Soil Fill

Depending on potential for moisture change—whether increase through gradual soaking or decrease by desiccation—the change in volume of fills made from expansive soils can be significant over several years. For example, a common CL-CH clay with a PI of 30, compacted to 90% ASTM D1557 at 25% water content, will exhibit a swell pressure of about 144 kPa (3,000 psf) and will be subject to long-term swell of about 5% in the upper 3–4.5 m (10–15 ft) and compression of 2% or more will occur below 10 m (30 ft).

Volume changes occurring in the upper few feet beneath light loads will tend to be greatest both on account of lesser confinement and the higher probability of varying moisture environments. For example, with shallow foundations the differential movement between a northern shaded side of a house with irrigation and the opposing dry landscaped southern side of the same house can be shown in theory to be roughly 150 mm (6 in.); the writers have observed such movements to be about 75 mm (3 in.) in this common situation.

Hydrology

Postconstruction ground movements depend on cyclical moisture changes that are affected by local climate. The Bay Area climate is seasonal wet-dry Mediterranean with winter rains of 300–380 mm (12–15 in.) and mild dry summers. Pan evaporation is about 1.5 m (60 in.).

The seasonal "active zone" of surficial wetting and drying (with associated soil shrinkage and swell) is usually taken to be 0.9–1.5 m (3–5 ft) deep, though some recent observations suggest that longer-term weather cycles may lead to deeper changes, on the order of 3 m (10 ft) or more.

Troublesome bedrock is usually found in upland areas with deep permanent water tables. Soil suction tests at one such site with abundant claystone showed a general moisture deficiency with soil suction values for sandy claystone bedrock typically of $pF = 3.5–4$, or 300–1,000 kPa (6,000–20,000 psf). Compacted fill derived from the same materials exhibited values in the same range. This was in an area that had been developed in the 1970s. Damage was continuing even into the 1990s. A decade of construction disturbance and irrigation had not provided enough moisture for full equilibrium swelling. Some 400 houses in this subdivision, including houses on cut and on fill, had soil damage claims. House level surveys showed vertical misalignments in the range of 40–100 mm (1.5–4 in.).

Local variations in soil moisture are induced by irrigation (often excessive), which creates spotty wet areas in landscaping near and beneath foundations. Local desiccation is common in dry sideyards with extra heat reflected from south-facing walls. Given the variations around the perimeter