Characterization and Settlement Modeling of Deep Inert Debris Fills

Caractérisation et modélisation du tassement de dépôts épais de gravats inertes

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ABSTRACT: Inert debris fills are difficult to characterize and model by normal geotechnical methods, due to their inherent heterogeneity, very large particle size, and nested and voided structure. The approach taken to characterize a 54 m deep inert debris fill, model its settlement behavior under seismic loading and groundwater level rise, and develop remedial measures to render it suitable for development is presented. Fines migration into open cavities and collapse of nested structure were determined to be the primary settlement mechanisms for this material. An upper bound estimate of cavity volume vulnerable to fines migration and collapse was made based on the results of large scale in-situ density and gradation tests. Settlement was estimated for various percentages of cavities becoming filled, and compared to case histories of dry fill settlement from the San Fernando and Northridge earthquakes. The proposed remedy involved partial removal of the debris fill and replacement as a compacted fill cap to attenuate the surface expression of differential settlement occurring in the underlying debris fill. Surface manifestation of settlement was simulated using FLAC. Charts were developed relating cap thickness to surficial manifestation of differential settlement.

RÉSUMÉ : Les dépôts de gravats inertes sont difficiles à caractériser et à modéliser par les approches géotechniques usuelles, en raison de leur hétérogénéité intrinsèque, de la grande taille des particules qui les constituent, et de leur structure lacunaire et emboîtée. On présente une approche utilisée pour caractériser un dépôt de gravats inertes de 54 m d'épaisseur, modéliser son comportement de tassement sous chargement sismique et sous l'effet d'une montée du niveau de la nappe phréatique, et développer des mesures de remédiation en vue de le rendre propre à l'utilisation. On a pu montrer que la migration des fines dans les cavités ouvertes, et l'écrasement des structures emboîtées, constituent les mécanismes principaux responsables du tassement pour ce matériau. Une estimation par excès du volume des cavités vulnérables par la migration des fines et écrasement a été établie sur la base d'essais à grande échelle de densité in-situ et de granulométrie. Le tassement a été estimé pour divers proportions de remplissage de cavités, et comparé à des observations historiques de tassement de remblais secs suite aux séismes de San Fernando et de Nothridge. Le remède proposé implique un retrait partiel du dépôt de gravats et son remplacement par une couche de remblai compacté, en vue de minimiser l'expression en surface des tassements différentiels survenant dans le dépôt de gravats sous-jacent. Le déplacement en surface a été simulé en utilisant le logiciel FLAC. La relation entre l'épaisseur de la couche de protection et l'incidence en surface du tassement différentiel a été exprimée sous forme d'abaques.

KEYWORDS: inert debris landfills; debris fills; seismic settlemen

1 INTRODUCTION

Inert debris landfills in urban areas are increasingly becoming potential sites for industrial / commercial redevelopment due to scarcity of vacant land and a desire by local communities to turn blighted areas into revenue sources. These fills, generally placed in abandoned mine pits, could be over 50 m deep and typically consist of uncontrolled fills of construction and demolition (C&D) debris. Due to their inherent heterogeneity and very large particle size they are difficult to characterize and model by normal geotechnical methods. This case study presents the approach taken to characterize a deep inert debris fill, model its settlement behavior under seismic loading and groundwater level fluctuations, and develop remedial measures to render it suitable for development.

The inert debris fill, located in the City of Irwindale in southern California, consists of over 8 million cubic meters of C&D waste placed over a period of 15 years within a 54 m deep abandoned open pit gravel mine covering a footprint of 22 hectares. The lower 2 to 12 m of the pit was filled with hydraulically placed silt, a by-product of aggregate mining operations. Review of placement records indicated that the inert debris fill above the silt layer consists of a succession of 1 to 3 m thick lifts of rubble consisting mostly of broken concrete, brick, tile and asphalt capped with 15 to 30 cm thick lifts of sandy and silty soils. The soil layers were generally placed and compacted above each rubble lift to provide a suitable surface for rubber tired traffic. The entire inert debris fill is capped with a 3 m thick layer of compacted soil to allow for utility excavation and structure foundation at the finished surface. Placement records indicate that initially the rubble fills were placed with some degree of material processing (crushing of oversize concrete clasts) and compaction. However, much of the inert debris fill was loosely end dumped with little or no control of lift thickness, particle size or compaction. The groundwater level was approximately 36 m below the ground surface during filling, but could rise by about 12 m based on historic records. An idealized profile of the fill stratigraphy is shown in Figure 1.

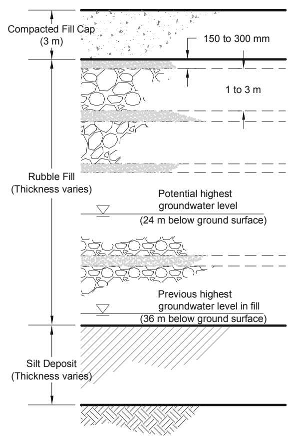

Figure 1. Debris Fill Stratigraphy

The site is vulnerable to relatively high levels of seismic loading, with a design peak ground acceleration of approximately 0.53g per the building code. Deaggregation analysis indicated the corresponding moment magnitude to be 6.7. The area is zoned for industrial or commercial development. The owners are evaluating remedial measures to make the site suitable for building development.

There are no industry-accepted standards or case histories to predict settlements of inert debris fill containing significant oversize fragments and significant open cavities. Case histories of seismic settlements of unsaturated fills are generally limited to earthfill/rockfill dams and compacted soil fills. Laboratory cyclic simple shear test data relating cyclic shear strain to volumetric strain, that may be used to estimate the settlement of unsaturated fills under seismic shaking, are limited to sands (Silver and Seed 1971, Pyke et al 1975), and finer grained compacted fills (Stewart et al 2002). Charles (2008) documents case histories of long-term settlement and collapse potential of uncontrolled opencast mining backfills in Britain. The City of Irwindale is currently conducting a laboratory study to evaluate the potential for wetting induced settlements (hydrocollapse) in inert debris fills.

2 FIELD INVESTIGATIONS

Field investigations for this site included Becker hammer borings, surface and downhole geophysical surveys, downhole video logging, test excavations and large scale in-situ density and grain size distribution tests. Neither the Becker penetration tests (BPTs) nor the surface and downhole seismic surveys, proved to be suitable to characterize the heavily nested and voided nature of the fills. The presence of very large size fragments appear to significantly skew the measured Becker blow counts and shear wave velocities, making these methods incapable of adequately differentiating between well compacted, grading code - compliant fills (derived from the same debris materials), and the loose debris fills with voids/cavities. This conclusion has been confirmed by studies performed by the City of Irwindale at other debris fill sites (Geomatrix, 2007).

Mapping of two deep test excavations to 21 m depth in the poorly controlled debris fill, confirmed the layered filling pattern consisting of thick rubble fill lifts capped by thin soil layers. The layered filling pattern was also apparent in the BPT logs. The rubble fill consisted of concrete clasts and blocks up to 2 m in size (with abundant rebar), mixed with brick, tiles, asphalt concrete, crushed glass and variable amounts of soil infill. Large voids, cavities and nesting were very common.

Eight large diameter ring density tests (1.8 m diameter x 1.5 m deep) performed as per ASTM D5030 in the inert debris fill at various depths (ranging from 5 to 15 m below ground surface) in the test excavations, and eight sand cone tests performed on soil layers or soil rich fills gave the following results.

Table 1. Results of In-situ Density Tests

Material	In-situ Dry Density (gm/cc)		Average Void Ratio
	Range	Average	
Inert Debris Fill	1.22 – 2.03	1.77	0.43 (e_t)
Soil Layers	1.45 – 1.86	1.64	0.62 (e_s)

The in-situ densities of the inert debris fill were compared to field maximum achievable density (MAD) tests performed on inert debris materials placed in 30-cm thick lifts and compacted by 50 passes of heavy earthmoving equipment (combination of Caterpillar 820 front end loader and 825 compactor). The corresponding MAD dry densities ranged from 2.03 to 2.13 gm/cc.

A qualitative evaluation of the voided / nested structure of the inert debris fill was performed by measuring the rate of water percolation in large diameter test holes. After completing the large diameter in-situ density tests, the plastic sheeting used to line the test hole was pulled out and the water level drop was monitored. The water levels dropped very rapidly (emptied in a matter of minutes) in test holes in debris fills, while the water levels stayed full for several days in the MAD tests holes, confirming the presence of significant voids / cavities in the debris fill.

Field bulk gradation tests performed on the bulk samples excavated from the density test pits showed the following distribution:

Table 2. Summary of Field Gradation Test Results

Material Size	Range (%)	Average (%)
Boulders (>300 mm)	3 to 23	11
Cobbles (>75 mm)	10 to 25	18
Gravels (>19 mm)	6 to 20	14
Finer than (19 mm)	44 to 66	57

Visual observations of the materials removed from the test excavations suggest that the oversize fraction is greater than the amounts listed above, since representative amounts of very large concrete clasts could not be included in the material from 1.5 m diameter test holes. The actual boulder size fraction (> 300 mm) was estimated to be in excess of 20 percent by weight.

3 SETTLEMENT MODEL

The settlement model used in the analysis considered the layered nature of the debris fill consisting of a succession of 1 to 3 m thick voided and nested rubble lifts capped by 15 to 30 cm thick loose to medium dense soil lifts. The total debris fill may be considered to consist of nested oversize clasts (defined as materials lager than 19 mm for purposes of this analysis), infill soils (minus 19 mm fraction that partially fills the cavities between clasts and also caps individual layers of rubble), and cavities (Figure 2).

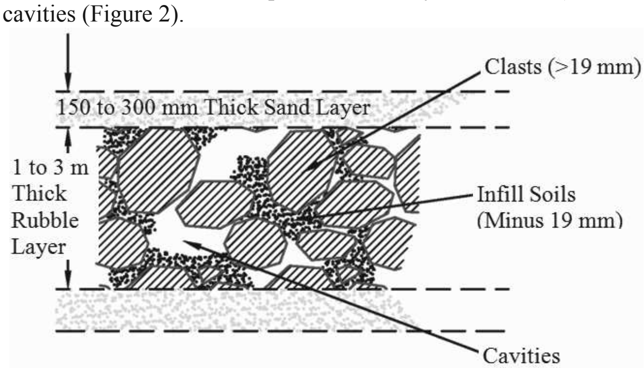

Figure 2. Debris Fill Structure

When subjected to seismic loading and/or saturation due to groundwater rise, the predominant mechanisms of settlement in the debris fill are considered to be partial filling of the cavities by fines migration (cap soils migrating into the underlying nested rubble), and collapse of the nested structure. Volumetric compression of the infill soils and soil lifts will also take place, but they are considered to be significantly smaller than the two dominant settlement mechanisms. The volume of cavities between the nested clasts, as a percentage of the total volume of fill, will, therefore, form an upper bound of the potential volumetric strain / settlement of the fill. The volume of cavities in the fill (Figure 2) as a ratio of the total fill volume, was estimated as shown below, based on the void ratio of the entire debris fill, e_t (calculated from large diameter ring density tests), void ratio of the infill soils, e_s (calculated from the sand cone density tests), the ratio of weight of clasts to weight of infill soils, R (from particle size distribution tests), and the specific gravity of the clasts (Gc) and infill soils (Gs).

The ratio of volume of cavities to volume of solids, e_c, and the relative volume of cavities with respect to the total volume for debris fill (Pc) may be expressed as:

$$e_c = e_t - e_s / (1+R.Gs/Gc) \quad (1)$$

$$P_c = e_c / (1+ e_t) \quad (2)$$

Based on the above equations, and using the average values of e_t (=0.43), e_s (=0.62), R (43%/57% = 0.75) and specific gravity (Gs = 2.65; Gc = 2.4), the average volume of cavities within the poorly controlled debris fills was calculated at 6.6% of fill volume. The calculated volume of cavities agrees well with field experiment estimates of cavity volume made at other inert debris fill sites in Irwindale with similar materials and filling practices. Those evaluations included a controlled in-situ pilot grouting test which resulted in a grout take of 4.4 to 7.2% of total volume, and an in-situ dynamic compaction test which resulted in a volume reduction of 5 to 7% of total fill volume (AMEC, 2008).

However, not all of the calculated cavity volume is available for fines migration / collapse. Actual volumetric strain and the resulting settlement is proportional to the volume of cavities that are closed or filled with fines in the event of an earthquake or hydrocollapse caused by rise in groundwater level. This is a function of many factors including the grain size distribution of the oversize clasts, accessibility of cavities to overlying infill soils, cohesion of infill soil and intensity and duration of seismic shaking, and cannot be reliably estimated in the absence of material-specific physical modeling. Therefore, a parametric settlement evaluation considering various percentages (p) of total cavity volume becoming filled was performed. The results are summarized as average settlement versus depth plots (Figure 3). The settlements shown in Figure 3 for each value of p, represent the average of the calculated settlements at six BPT locations across the site. Although the total thickness of debris fill was similar at each location (approximately 33 m), the thickness of the poorly controlled, layered rubble fill vulnerable to fines migration/collapse was variable (ranging from 15.6 to 25.0 m).

The average settlement corresponding to 20% of cavities filled (p = 20%), was computed at 28 cm (approximately 1.32% of poorly controlled debris fill thickness or 0.85% of total debris fill thickness). The latter value compared favorably with some case histories of dry compacted fills in southern California which settled by 0.6 to 0.9 percent of fill thickness during the M6.6, 1971 San Fernando, and the M6.7, 1994 Northridge earthquakes, under ground accelerations comparable to the design ground motions for the site. Considering the significant heterogeneity of the debris fills, the seismic settlements could be higher or lower than that predicted for p = 20%. To bracket this uncertainty, seismic settlements under the design earthquake were calculated for 'p' ranging from 10% to 30%. The resulting settlements ranged from 0.4 to 1.1 percent of total debris fill thickness.

A 12 m thick zone of debris fill immediately above the current groundwater level could become saturated if the groundwater level was to rise to the historic high groundwater level. This zone has not been saturated since the time of placement. Settlement due to groundwater saturation was considered to result from the same mechanisms of fines migration and collapse, and was assumed to be of the same order of magnitude as the seismic settlements. These settlements, estimated to range from 75 mm to 150 mm, occur approximately 24 m below ground surface (the depth of the high groundwater level below ground surface). Because the same mechanisms (migration of sands into open voids and collapse) apply to both seismic settlement and settlement due to groundwater rise, the two components of settlement (seismic and hydrocollapse) are not considered to be cumulative.

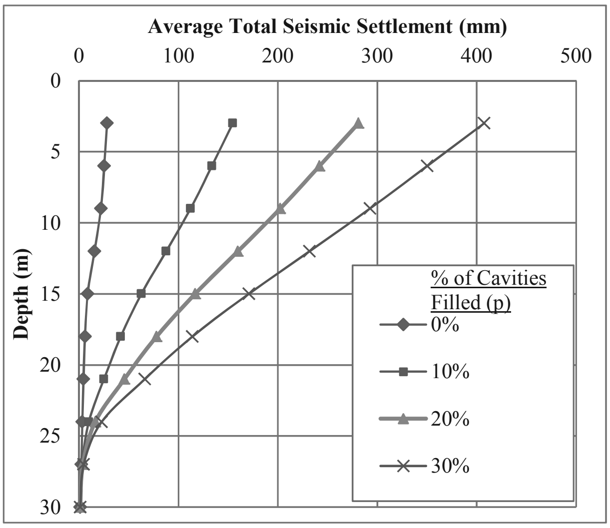

Figure 3 Distribution of Seismic Settlement with Depth

4 REMEDIAL MEASURES

The remedial measures recommended for limiting settlement at the site to within agency-defined guidelines or structural tolerances, consisted of partial removal of the existing debris fill and replacement with a properly processed and compacted fill cap. The required cap thickness could also be achieved by a shallower removal and replacement combined with in-situ ground improvement of the lower part of the debris fill by dynamic compaction. With increasing thickness of cap, the fill thickness left in place that is vulnerable to settlements would decrease. The cap will also help attenuate the differential settlement taking place at depth as it manifests at the surface of the fill cap.

The surface manifestation of settlement was simulated by numerical modeling using FLAC. A representative two-dimensional cross section across the entire site was considered. The fill cap was modeled as a non-linear elastic – perfectly plastic Mohr-Coulomb material. The initial shear modulus for the cap was based on the average shear wave velocity of 268 m/sec measured in the compacted fill. The modulus degradation curve was based on the Seed-Idriss relationship for sand. The calculated seismic / hydrocollapse settlement of the debris fill underlying the fill cap, was applied as nodal displacement boundary conditions at the base of the cap. Since the thickness of poorly controlled rubble fill and the corresponding settlements are variable across the site, the nodal displacements were specified as randomly varying over the range of settlements calculated at the 6 BPT locations.

The nodal displacements (ρ_n) were generated as follows:

$$\rho_n = \rho_{min} + r. (\rho_{max} - \rho_{min})$$

where, r is a random number between 0.0 and 1.0 (determined by a random number generator for the numerical analyses) and ρ_{min} and ρ_{max} are the minimum and maximum values, respectively, of calculated seismic/hydrocollapse settlements, for a given value of p. The specified random nodal displacements were applied at 1.5 m horizontal intervals along the base of the cap. The modeling was performed for p = 10%, 20% and 30%.

Typical FLAC analysis results as illustrated in Figure 4, show the original and deformed shape (grid) of a segment of the fill cap as a result of the random differential settlement applied at the base of the cap, for cap thicknesses of 12, 18 and 24 m, respectively. As the fill cap thickness increases, the magnitude of the total and differential settlement of the material left in place decreases, and the attenuation of the surface manifestation of differential settlement increases. For the case illustrated in Figure 4, the differential settlement at the base of the cap decreases from 122 mm to 43 mm as the cap thickness increases from 12 m to 24 m. The corresponding maximum differential settlement at the surface (over a 9-m horizontal distance) decreases from 56 mm to 8 mm.

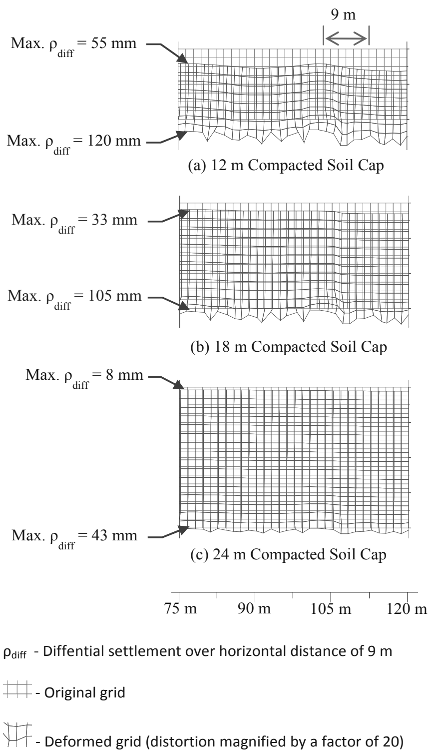

Figure 4. Sample Results from FLAC Analysis

The results of the surficial manifestation analyses, presented as plots of surficial total and differential settlements versus thickness of fill cap (for a range of assumed values of cavities filled by migration of fines and collapse, p), are plotted in Figure 5. This chart was used to select a suitable thickness of removal and replacement based on the differential and total settlement tolerance of the proposed structures.

5 CONCLUSIONS

The seismic and hydrocollapse settlement potential of uncontrolled inert debris fills containing significant oversize clasts could not be evaluated by conventional means. Laboratory testing of representative material was not feasible because of particle size limitations. BPTs and seismic shear wave velocity surveys were ineffective in differentiating well compacted fills from uncontrolled fills. An alternative approach consisted of the following steps:

- Based on the results of large scale in-situ density and grain size distribution tests, an upper bound estimate of cavity volume was made (approximately 6.6% of total debris fill volume).

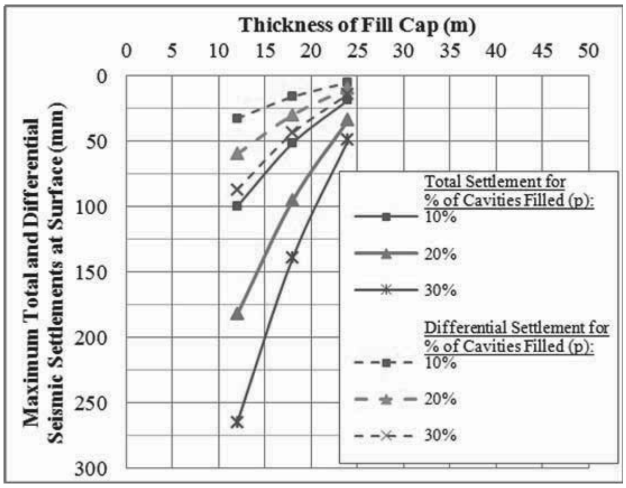

Figure 5. Surface Manifestation of Settlements

- A settlement model based on partial filling of cavities by fines migration and collapse of nested structure was developed. Parametric analyses of various degrees of cavities filling were performed to account for heterogeneity of the debris fill and to obtain a range of likely settlements. Estimated settlements due to seismic shaking ranged from 0.4 to 1.1 percent of total fill thickness with an average of 0.85%.
- The predicted settlements from this model were compared to published case histories of seismic settlement of unsaturated fills under earthquake ground motions similar to the design ground motions.

The proposed remedy for rendering the site suitable for building development was partial removal of the uncontrolled debris fill and replacement as a properly compacted fill cap. Based on numerical modeling, charts were developed relating thickness of fill cap to estimated surficial differential settlement. To meet local building code requirement of maximum 25 mm differential settlement over a 9-m length, 22 m of removal and replacement will be necessary. The depth of removal and replacement may be reduced, provided the differential settlement tolerance of the structure is increased by structural improvements such as stiffened foundation systems including mat foundations, post tensioned slabs and grade beams. The reliability of predictions by this approach may be increased by physical modeling of debris fill settlement under the effects of seismic shaking and saturation, and developing a database of observed settlements under moderate seismic events.

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