SOIL/STRUCTURE INTERACTION EFFECTS AT EL CENTRO, CALIFORNIA TERMINAL SUBSTATION BUILDING

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SUMMARY

This paper presents results of an analytical study of the dynamic response characteristics of the El Centro, California Terminal Substation Building – where a substantial number of "free-field" strong motion records have been measured. The objective of the study is to indicate the degree to which motions recorded in this building are affected by soil/structure interaction. Results of the analyses conducted under this study indicate important soil/structure interaction effects over a frequency range of importance in the seismic design of many structures.

INTRODUCTION

Many strong motion records currently used to represent free-field ground motions for seismic design purposes have been measured in basements of buildings. However, under certain conditions, soil/structure interaction may cause these basement motions to differ from those of the free field. This paper examines the possible extent of such differences at one particularly prominent accelerograph station – that in the basement of the Terminal Substation Building (TSB) in El Centro, California. This accelerograph station has contributed more records to the current library of strong motion data than any other station in the United States, and the records measured there during the 1940 Imperial Valley earthquake have been widely used as free-field seismic input motions for the design of major structures throughout the world.

GEOLOGIC SETTING

The city of El Centro is located in Southern California, about 120 miles east of San Diego. It lies in the Imperial Valley portion of the Salton Trough, a low-lying depression that is bounded by the Peninsular Ranges to the west and the Mohave Desert in the east. This region is cut by a number of recently-active, northwest-trending, right-lateral strike-slip faults or fault zones. It is one of the most seismically active areas of California and, in recent years, has been subjected to Magnitude 6.5 earthquakes along the Imperial fault near El Centro (in 1940 and 1979), along the Coyote Creek fault in the Borrego Mountains (in 1968), and along the San Jacinto fault in Mexico (in 1934).

STRUCTURE CONFIGURATION

The TSB accelerograph station is located near the intersection of Third Street and Commercial Avenue in El Centro. It consists of a two-story heavily

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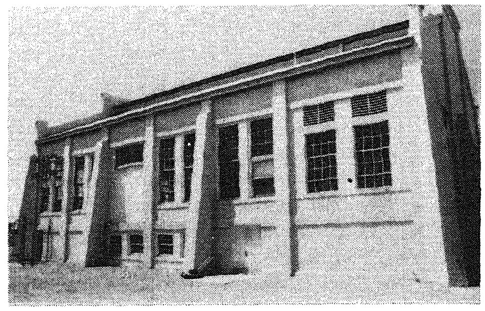
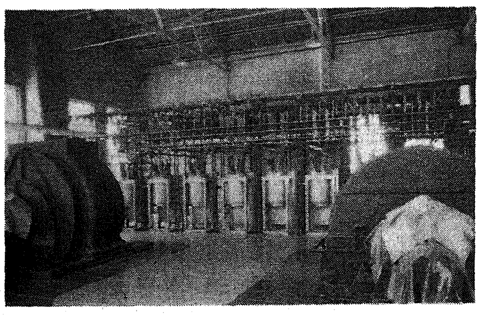
reinforced concrete structure with heavy walls strengthened at the sides and corners by massive buttresses, and a roof supported by a steel truss. The main floor slab supports large condenser units, with weights as large as 58,500 lbs (260,325 N) (Figs. 1 and 2).

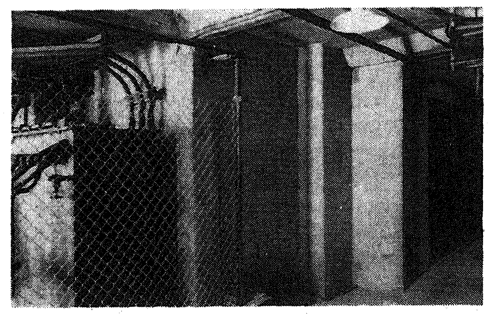
View Looking North



View Looking West

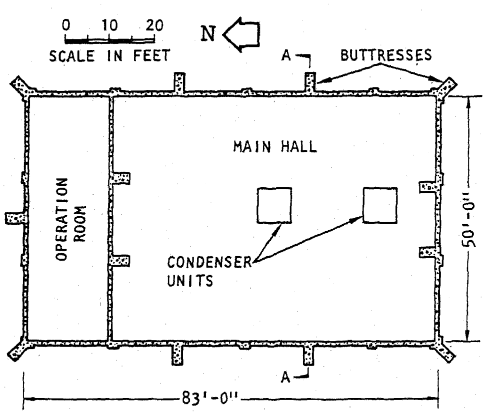


Main Floor

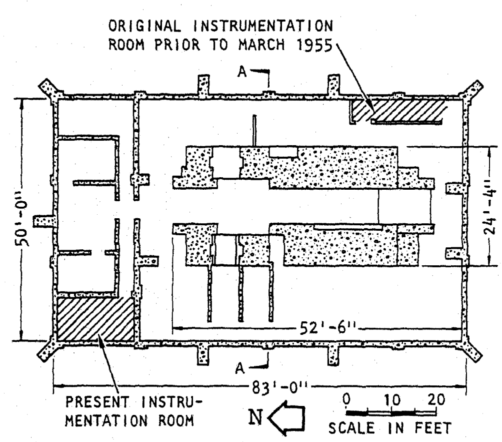


Instrumentation Room Entrance

FIGURE 1. EL CENTRO TERMINAL SUBSTATION BUILDING

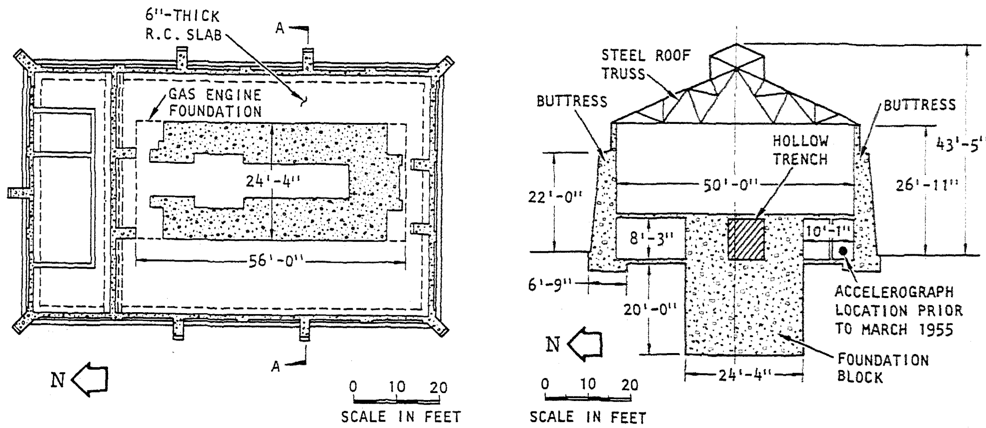


(a) Main floor plan



(b) Basement plan

FIGURE 2 PLAN VIEWS AND CROSS SECTIONS OF TSB



(c) Foundation plan (d) Section A-A

FIGURE 2. (CONCLUDED)

The building was originally designed to house a massive gas engine (removed in 1914). To fulfill this function, a special foundation for the engine was constructed as a massive block of concrete that extends 20 ft beneath the basement floor (Fig. 2d). Data describing the dimensions and depth of this block were available only in limited sketches (Ref. 1, 2). Therefore, because of the importance of the block for this particular study, its dimensions and properties were verified as part of this study using micro-reflection survey techniques (Ref. 2).

INSTRUMENTATION

The first instrument installed in the TSB (in 1932) was a Coast and Geodetic Survey strong-motion accelerograph located in the southeast corner of the basement. The shaking measured during the 1940 Imperial Valley earthquake was recorded on this instrument. This accelerograph was relocated to the northwest corner of the TSB basement in 1955 (Fig. 2b). This and other instrumentation contained in the TSB are described in Reference 2.

SUBSURFACE SOIL CONDITIONS

The subsurface soil conditions used as the basis of the soil models in this analysis were defined from special geotechnical investigations carried out in a companion study under this project (Ref. 3). The investigation included boring and sampling of the subsurface materials to a depth of 400 ft (122 m). Field and laboratory tests of these materials defined index properties, shear strengths, dry densities, and standard penetration resistances. In addition, dynamic soil properties were measured using in-situ impulse tests (Ref. 4) to depths of 140 ft (43 m), resonant column tests to depths of 180 ft (55 m), and cyclic triaxial tests of soil samples from depths of 40 ft, 115 ft, and 175 ft (12 m, 35 m, and 53 m).

The boring log and test results indicate that the TSB site is comprised primarily of silty clays within the 400 ft (122 m) depth of the boring (Fig. 3). Small-strain shear wave velocities range from about 500 fps (152 m/sec) near the ground surface to about 1400 fps (427 m/sec) at a depth of about

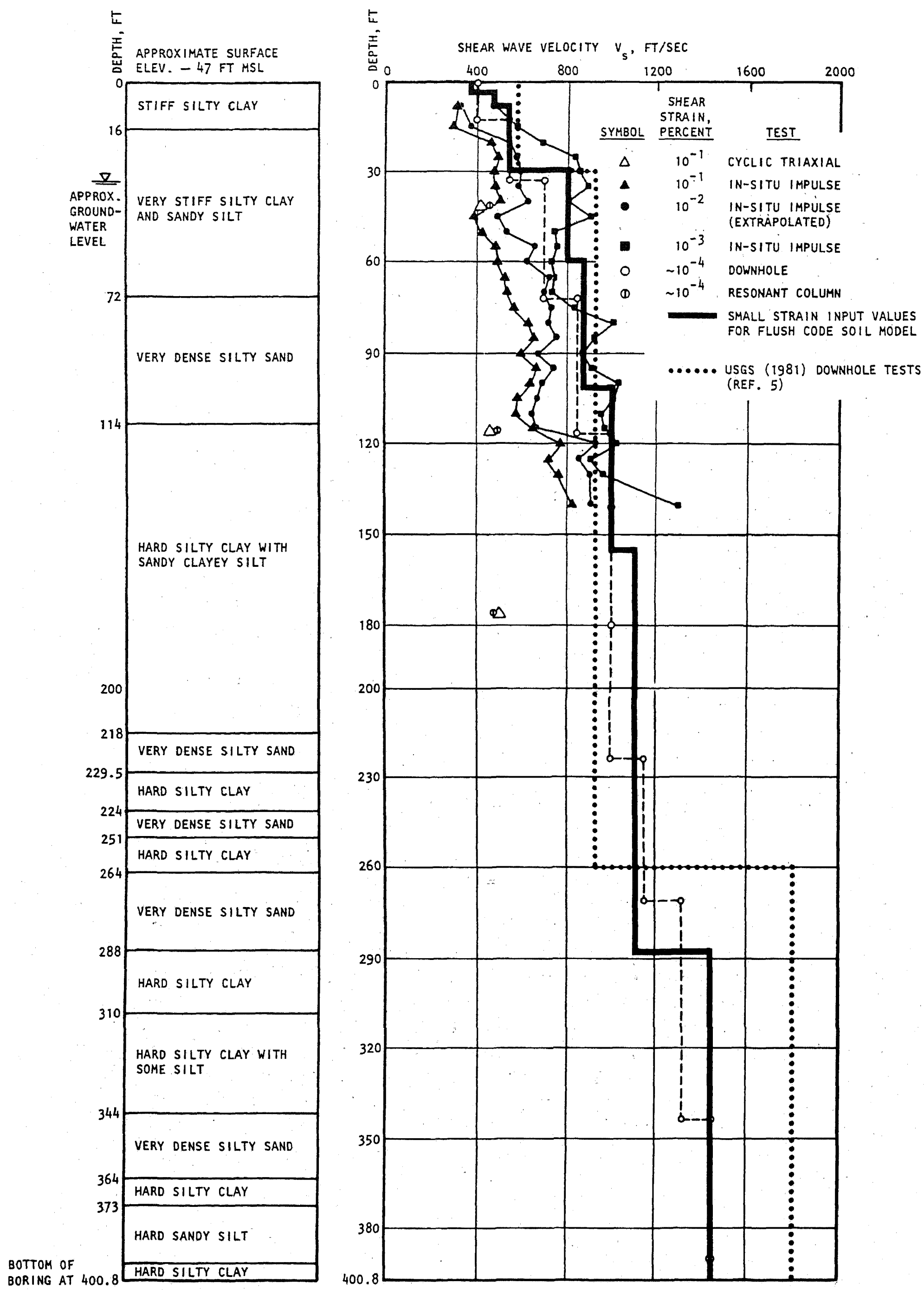


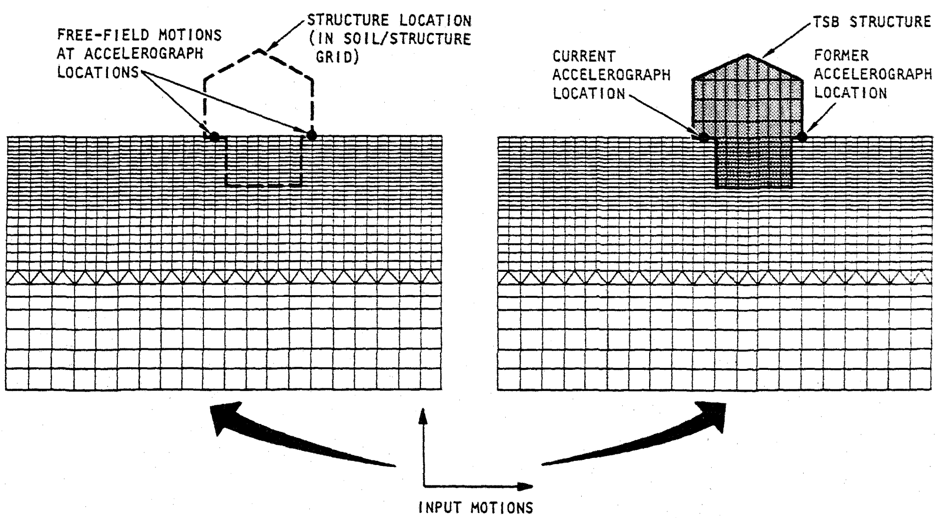
FIGURE 3. DYNAMIC SOIL PROPERTIES AT TSB SITE (Ref. 3, 5)

400 ft (122 m) (Ref. 3). Figure 3 shows that, except at substantial depths, these shear wave velocities compare well with results of downhole tests recently conducted at the TSB site by the United States Geological Survey (USGS) (Ref. 5).

ANALYTICAL PROCEDURE

To evaluate possible soil/structure interaction effects on the TSB response, dynamic analyses of the TSB and the adjacent free field were carried out. These analyses were performed twice using two different two-dimensional finite element approaches that represent different assumptions pertaining to the soil modeling and the incident wave motion. The first approach (FLUSH Code) is based on vertically-propagating incident shear wave motion, and on an equivalent-linear soil model whose properties are modified through successive iterations to be compatible with computed average dynamic shear strains induced in each layer by the input motions (Ref. 6). The second approach (TRI/SAC Code) can incorporate any type of incident wave motion, but considers an elastic model of the subsurface soil conditions (Ref. 7).

In each of the above finite element approaches, the following steps were carried out (Fig. 4): (1) through application of assumed seismic input motions to a finite element model of the soil profile, free-field motions were computed at the location of the TSB structure; (2) through use of the same seismic input motions and soil model in a finite element grid that now also contains the structure, the TSB basement response at the former and current accelerograph locations was computed; and (3) through comparison of the



(a) Soil grid (for free-field analysis)

(b) Soil/structure grid (for structure response analysis)

FIGURE 4. ANALYSIS PROCEDURE

results from Steps 1 and 2, the relative influence of soil/structure interaction on motions that might be recorded at the TSB was evaluated. The soil models used in these various analyses were based on properties derived from the geotechnical investigations described previously (see Fig. 3). The structure models, in turn, were based on the above-indicated foundation block measurements, and on TSB layouts and machinery weights, geometries, and locations obtained from: (1) detailed measurements obtained during a visit to the TSB as part of this study; (2) discussions with TSB personnel and with earthquake engineers familiar with the facility; (3) available TSB drawings; and (4) information contained in a USGS memorandum (Ref. 1). Details of these soil and structure modeling procedures are provided in Reference 2.

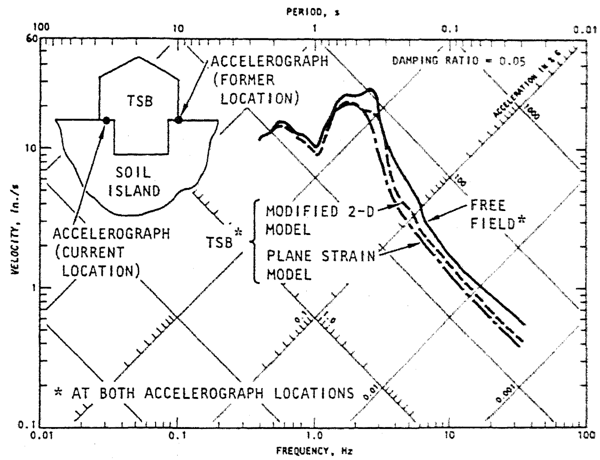
ANALYSIS RESULTS

Several sets of results describing the motions and states of stress computed from the free-field and soil/structure system analyses are described in Reference 2. However, the most important result for assessing possible soil/structure interaction effects at the TSB is the comparison of response spectra of motions computed at the accelerograph locations within the TSB to the spectra of motions at the corresponding locations within the free field. Separate response spectrum comparisons were obtained from each of the two finite element analysis approaches employed in this study. Furthermore, in the FLUSH Code approach, two different soil/structure system models were employed: one was a plane strain model and the other was a "modified two-dimensional (2-D)" model in which out-of-plane wave propagation effects were approximated by using in-plane viscous dampers at each soil node point. The TRI/SAC Code approach used a single soil/structure system model corresponding to a plane strain configuration.

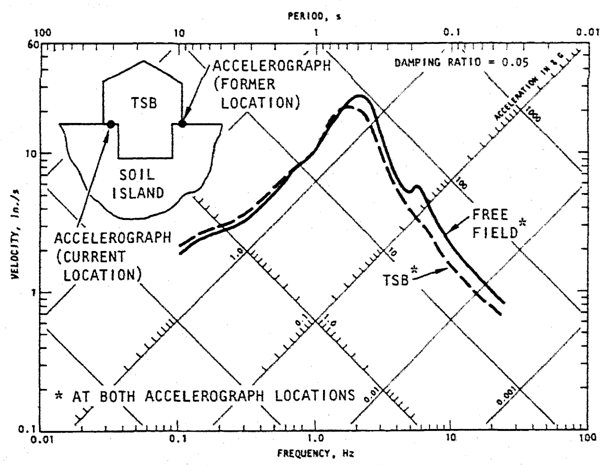
Response spectrum results from these analyses are presented here for horizontal motion comparisons only; additional results involving vertical motions are described in Reference 2. The trends from these results are essentially the same for each of the analysis approaches and modeling procedures (Fig. 5). They show that, at frequencies below about 1.5 Hz, the computed motions in the free field and at the accelerograph locations in the TSB basement are virtually identical. However, at higher frequencies, the computed motions at the TSB accelerograph locations fall below those of the free field, by factors typically ranging from about 20 percent to over 100 percent. Therefore, the computations indicate that soil/structure interaction could have an important influence on the mid-to-high frequency components of motion recorded in the TSB basement – components that could be important in the seismic design of major structures.

CONCLUDING REMARKS

The El Centro TSB has been one of the more prominent "free-field" accelerograph stations in the United States, both in terms of the number of strong motion records it has produced and the importance of these records for seismic design purposes. However, the particular foundation conditions at the TSB – i.e., its massive foundation block and its deep soil deposits of moderate shear wave velocity – suggest important soil/structure interaction effects that could cause motions measured at the TSB to differ from those of the free field. In fact, one could anticipate that such foundation conditions would have the greatest influence on the TSB basement motions at mid-to-high frequencies, causing them to be reduced relative to the free field because of



(a) FLUSH code results



(b) TRI/SAC code results

FIGURE 5. ANALYSIS RESULTS AT TSB ACCELEROGRAPH LOCATIONS

soil/structure interaction. The analysis results obtained from this study, although based on certain simplifications pertaining to the soil and structure modeling, support this physically plausible trend.

This trend has important implications. It shows that, if building basement motions are assumed to represent free-field motions at accelerograph stations where soil/structure interaction is important, the actual free-field ground shaking can under certain conditions be underestimated over frequency ranges of importance in seismic design. Therefore, the potential presence and consequences of soil/structure interaction should be carefully considered, both when interpreting existing basement motion records and when planning the deployment of future free-field accelerograph stations. This will enhance our ability to further develop the free-field strong motion data base, and to properly implement it as a basis for obtaining meaningful seismic input criteria for design of earthquake-resistant structures.

ACKNOWLEDGEMENT

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