SOIL–STRUCTURE INTERACTION IN STEEL BRACED STRUCTURES WITH FOUNDATION UPLIFT

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ABSTRACT

In order to understand the structural behavior, it is useful to study the effects of soil-structure interaction. But usually soil-structure interaction studies are done with the assumption that foundation is fixed to the soil. During strong earthquake motions, uplift in some parts of the foundation may occur depending upon the type of soil which structure is located on. This paper investigates the nonlinear behavior of various steel braced structures placed on different types of soil with varying hardness. This can help in better understanding of the actual behavior of structure during an earthquake. Results showed that for structures allowed to foundation uplift, the softer the soil, the higher will be changes in seismic response.

Keywords: *Soil-structure interaction, Foundation uplift, Steel braced structures, Non-linear dynamic analysis.*

1. INTRODUCTION

To better understand the structural behavior, it is useful to study the effects of soil-structure interaction. But usually soil-structure interaction studies are done with the assumption that foundation is fixed to the soil. But during the Kobe, Japan's earthquake in 1995, some buildings under intensity VII earthquake, experienced less damage. Analysis of these structures using the model with fixed foundation showed that the damage measured by the model was higher than the damage experienced by the actual structure [1]. Such observations led researchers consider to this aspect of the structural behavior. In 1975, Meek dynamically analyzed the model which caused the uplift with one degree of freedom. He concluded that the foundation uplift, leads to a decrease in the maximum displacement of the structural [2]. Yim and Chopra studied the structures with one degree of freedom and concentrated mass. In their study, they examined effects of earthquake intensity, geometric parameters, and plasticity of soil on the structures with foundations uplifted. They concluded that foundation uplift decreases displacement and base shear [3]. In addition, Yim and Chopra studied structures with a few degrees of freedom. The system they studied was a shear frame. The foundation was modeled with two elements spring – damper. Structural response, which the foundation was allowed to uplift, was investigated in this case that led to a simplified method for systems with few degrees of freedom with uplift in their foundation [4]. Psycharis studied a building that had been a shear frame model with n degrees of freedom. Foundations and soil under the structures came to model into spring damper system that was uplifted. Analyses of results for this model indicate that the dynamic behavior of structures allowed to uplift may be very different in a model without foundation uplift. He concluded the foundation uplift often causes a reduction in structural responses, and these results can be affected by structural parameters and change the nature of stimulation [5]. Spyrakos and Chaojin analyzed systems that had been modeled for one degree of freedom under the influence of different factors such as the ratio of structure height to foundation width, soil hardness and type of foundation. They concluded that foundation uplift does not always lead to better structural response which must be noted. The effects of soil stiffness on a short tower are greater than on a slender one. The height-width ratio affects the seismic response of the tower significantly, especially for a tower at a rock-like location. The allowance of foundation uplift may substantially reduce the seismic response of moment and foundation rotation in the case of hard soil and a slender tower, or may greatly increase the seismic response of shear in the case of hard soil and a short tower. The study concludes that uplift is not always beneficial and its effects could be significant for structures under strong seismic motions [6]. Midorikawa et al were asked to evaluate the seismic response of steel frames about one-third of a three-story with columns allowed to uplift and compared with that of fixed-base frames by three-dimensional shaking table tests. The results are summarized as follows: the maximum base shears of the rocking frames are effectively reduced from those of the fixed base frames in longitudinal and transverse directions; the response deformations of the superstructures of the rocking frames excluding the rocking component are nearly equal to or smaller than the elastic response values of the fixed-base frames; and, the maximum column tensile forces for the rocking frames are limited to a relatively constant value less than those for the fixed-base frames after the uplift motion occurs, whereas the maximum compressive forces are almost equal to or less than those for the fixed-base frames [7]. Apostolou et al evaluated the rocking of rigid structures uplifting from their support under strong earthquake shaking. The structure is resting on the surface of either a rigid base or a linearly elastic continuum. A large-displacement approach is adopted to extract the governing equations of motion allowing for a rigorous calculation of the nonlinear response even under near-overturning conditions. Directivity affected near-fault ground motions, idealized as Ricker wavelets or trigonometric pulses are used as excitation. The conditions under which uplifting leads to large angles of rotation and eventually to overturning are investigated. A profoundly nonlinear rocking behavior is revealed for both rigid and elastic soil conditions. This geometrically nonlinear response is further amplified by unfavorable sequences of long-duration pulses in the excitation. Moreover, through the overturning response of a toppled tombstone, it is concluded that the practice of estimating ground accelerations from overturning observations is rather misleading and meaningless [8]. Butterworth et al presented a new method for modeling the dynamic response of rigid structures with uplift. The proposed technique exploits the use of a two-spring foundation, and subsequently an equivalent single-degree-of freedom procedure is established to model the dynamics of the system. They presented numerical examples on the use of the proposed procedure to simulate the dynamic response of uplifting rigid structures subjected to base excitation. These examples showed the model produced rational results which compared well with published experimental data [9]. Hashemi et al the effect of uplift on earthquake response of building was studied by earthquake response analysis. Finite element method was used for analysis. They concluded that, uplift reduced shear story force. Also effects of some parameters such as: slender of structure, elastic modulus of soil and cohesion coefficient of soil on foundation uplift was studied. Finally, earthquake response of models, assuming linear behavior for materials was compared with earthquake response of models, that their materials behavior was nonlinear [10].

2. SOIL-STRUCTURE INTERACTION

The estimation of earthquake motions at the site of a structure is the most important phase of the design or retrofit of a structure. Because of the large number of assumptions required, experts in the field often disagree, by more than a factor of two, about the magnitude of motions expected at the site without the structure present. This lack of accuracy about the basic input motions, however, does not justify the introduction of additional unnecessary approximations in the dynamic analysis of the structure and its interaction with the material under the structure. Therefore, it will be assumed that the free-field motions at the location of the structure, without the structure present, can be estimated and are specified in the form of earthquake acceleration records in three directions. It is now common practice, on major engineering projects, to investigate several different sets of ground motions to consider both near fault and far fault events. If a lightweight flexible structure is built on a very stiff rock foundation, a valid assumption is that the input motion at the base of the structure is the same as the free-field earthquake motion. This assumption is valid for a large number of building systems because most building type structures are approximately 90 percent voids, and it is not unusual for the weight of the structure to be equal to the weight of the soil excavated before the structure is built. However, if the structure is very massive and stiff, such as a concrete gravity dam, and the foundation is relatively soft, the motion at the base of the structure may be significantly different from the free-field surface motion. Even for this extreme case, however, it is apparent that the most significant interaction effects will be near the structure and, at some finite distance from the base of the structure, the displacements will converge back to the free-field earthquake motion [11].

3. MODELING

To meet the objectives of this study, a coordinated plan, as shown in Figure 1 is used. As indicated on the figure, the plan consists of 3 four meter aperture on the width side and 4 three meter aperture on the length side of the plan. Number of floors for models included 3, 6, and 12 floors and the height for each story was 3 meters. As a result, the height for structures is 9, 18, and 36 meters respectively. For the lateral restrain system, X-bracing (CBF), Chevron bracing (CHEVRON), Eccentric bracing (EBF) is used, as shown in Figure 2.

The aforementioned structures are designed for residential use and caries a dead load of 550 kilograms per squared meter and live load of 200 Kg/m^2 for floors and dead load of 500 Kg/m^2 and live load of 150 Kg/m2 for the roof. The structures were designed based on Iranian earthquake code of 2800[12]and Tenth of the Iranian national building code [13], for a region with a relatively high possibility of earthquake with acceleration of 0.3g.

After a complete design, SAP2000 software was utilized to perform a non-linear dynamic analysis of the structures for the case fix foundation. The accelerograph used for this study was the Tabas earthquake accelerograph as shown in figure 3. Then, structures are analyzed for non-linear dynamic foundation uplift. To model the foundation, flexible foundation method is employed. In the rigid foundation method, it is assumed the foundation is completely rigid and the pressure is distributed in a linear fashion under the foundation. Location and direction of the net pressure in the foundation is in the same direction as the applied loads. In the flexible foundation method, soil is considered as a collection of close elastic springs. The resulted model is called Winkler foundation and is depicted in Figure 4. The elastic coefficient for this assumed spring is called coefficient of sub grade reaction, ($K^{'}$) [14].

Foundation is like a tape for all models. The foundation canal for a three story structure has 120 cm width and 70 cm depth. For six and twelve story structures the width is 120 cm and 200 cm; and depth is 180 cm and 200 cm respectively. The spring stiffness is determined by the following equation:

$$K = b \times K' \quad (1)$$

Where K is the stiffness of the spring; b is the width of the foundation; and K' is the coefficient of reaction of the foundation sub grade or hardness of the soil. To show the hardness of the soil, soil1 with hardness of $K' = 3.204$ Km/cm^3 ($200\ Kip/ft^3$) and soil2 with hardness of $K' = 12.815$ Km/cm^3 ($800\ Kip/ft^3$) were used. These values have been selected to illustrate the range of medium to high of sand soil [15].

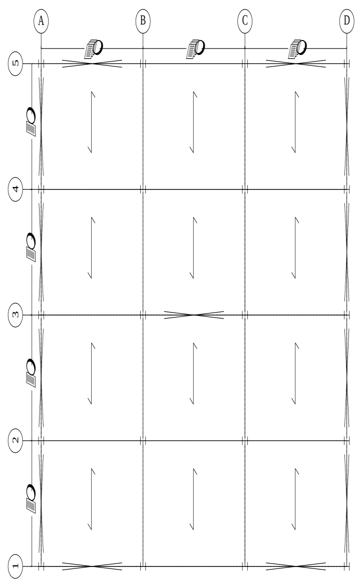

Figure 1 - Plan and Geometry Structure Model

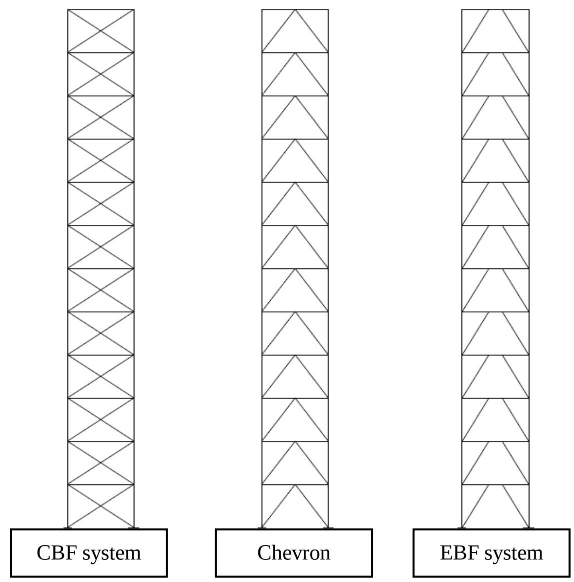

Figure 2 - Structural Systems in height

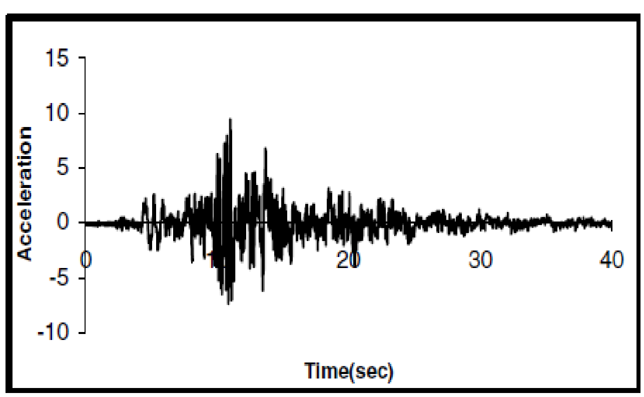

Figure 3 – Accelerograph of Tabas earthquake

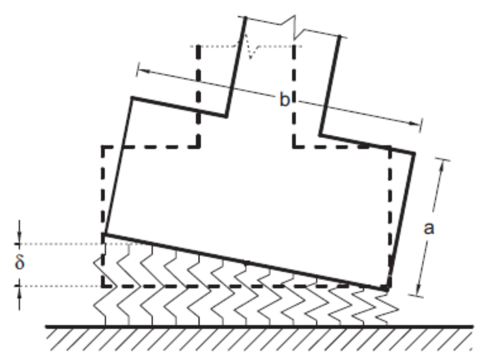

Figure 4 – Winkler Foundation Model

4. RATE OF UPLIFT

In this part uplift rates for various structures in foundations placed on the soil1 and soil2 were compared together. Maximum uplift was observed in the part of foundation located in the side axis of structures and they carried the brace load also. According to the values of tables shown below it is observed that with an increase in structure's height, rate of foundation uplift will also increase. Results of analysis show that levels (rate of) uplift in soft soil is more than stiff soil. The maximum difference in rate of uplift between the two soils is related to CBF system. Table values represent the rate of foundation uplift in EBF system is more than Chevron system. And this value is greater in Chevron system when compared with CBF system.

Table 1 - Comparison of uplift in the three-story structures

Uplift (mm)	CBF	Chevron	EBF
Soil	0.404	0.508	0.970
Soil2	0.176	0.237	0.441
Dif(%)	56	53	54

Table 2 - Comparison of uplift in the six-story structures

Uplift (mm)	CBF	Chevron	EBF
Soil	1.254	1.443	1.969
Soil2	0.513	0.618	0.918
Dif(%)	59	57	53

Table 3 - Comparison of uplift in the twelve-story structures

Uplift (mm)	CBF	Chevron	EBF
Soil	3.274	3.397	3.692
Soil2	0.981	1.079	1.312
Dif(%)	70	68	64

5. PERIOD

Figs. 5, 6, and 7 show the period for twelve-story structures with various braced systems. Numbers of optional modes chosen to study period were equal to the number of floors of the Structure. As the graphs show, foundation uplift causes the period to increases. According to the graphs, period decreases with increasing soil stiffness. Also the amount increase of period in structures allowed to foundation uplift for structures with EBF system is higher than structures with CBF system.

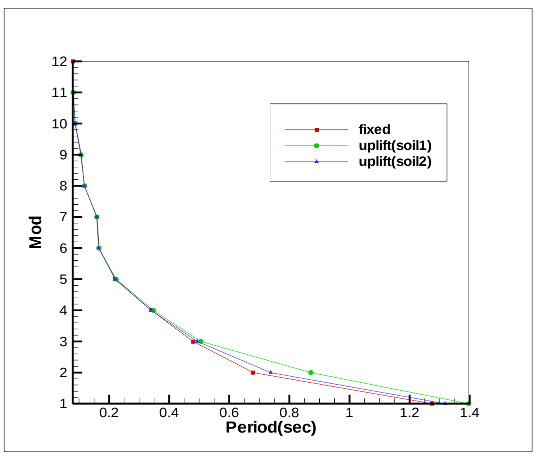

Figure 5 – Period for twelve-story structure with CBF system

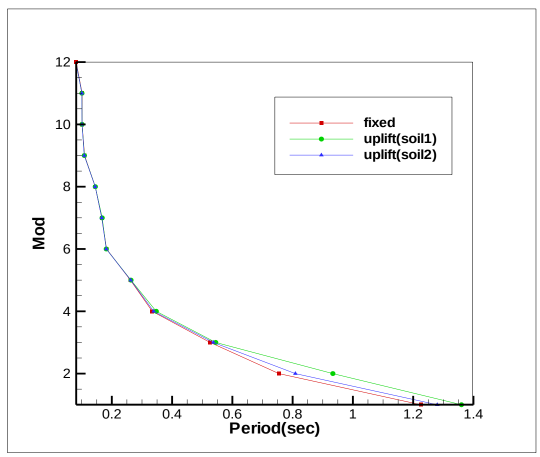

Figure 6 – Period for twelve-story structure with chevron system

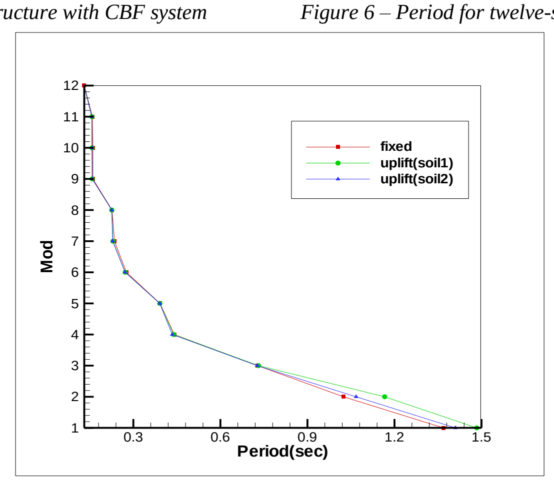

Figure 7 – Period for twelve-story structure with EBF system

6. BASE SHEAR

Since in structures allowed to foundation uplift the rigidity of whole structure becomes less in dealing with lateral loads. Therefore, it is expected that uplift causes a reduction in value of base shear in most structural conditions. Thus to check this matter, time history of base shear is compared in two modes, with or without foundation uplift in the various structures. Results show that decrease or increase in the value of base shear force depends on the number of floor structure and rigidity of soil. Due to the large number of charts, only three charts related to twelve floor structures are presented here. Foundation uplift causes the base shear force to reduce on three and six-story structure. This decrease is greater for the structure located on soil1; and the harder the soil the less likely that the structure will uplift. But Figures 6 and 7 and 8 shows for twelve-story structure the value based shear force does not change considerably in two modes, fixed foundation and foundation allowed to uplift.

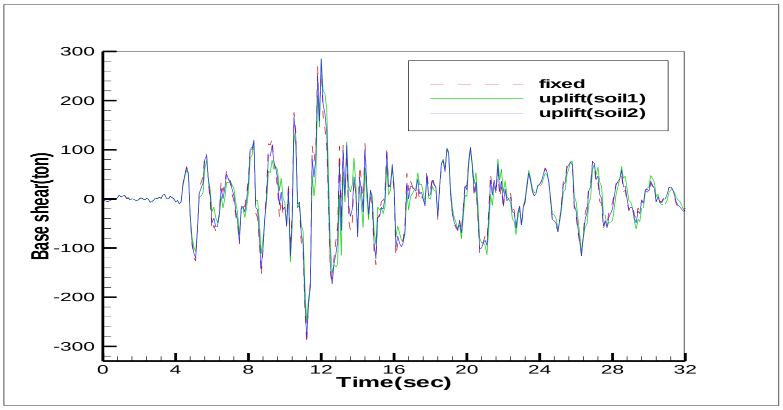

Figure 8 – Base shear for twelve-story structure with CBF system

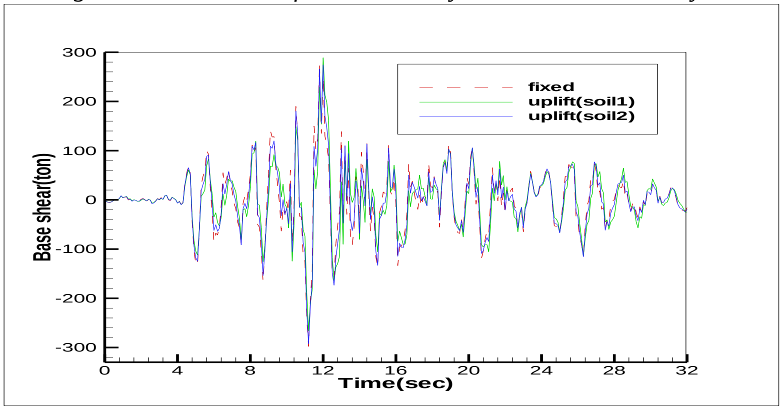

Figure 9 – Base shear for twelve-story structure with chevron system

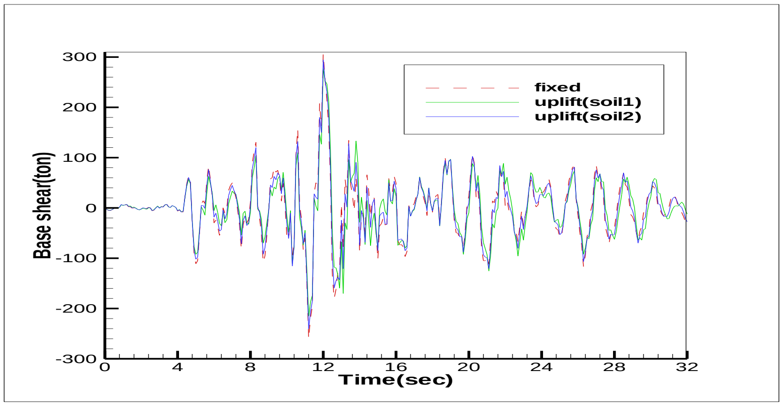

Figure 10 – Base shear for twelve-story structure with EBF system

7. STORY DRIFT RATIO

Story drift ratio is the maximum relative displacement of each floor divided by the height of the same floor is another important parameter that has been evaluated. It is observed that floor displacement increases when foundation is allowed to uplift, compared to fixed foundation. This displacement increase occurs in all types of systems. Figures 9, 10 and 11 represent the displacement increases more in foundations located on soft soil and this value decreases with increasing soil rigidity.

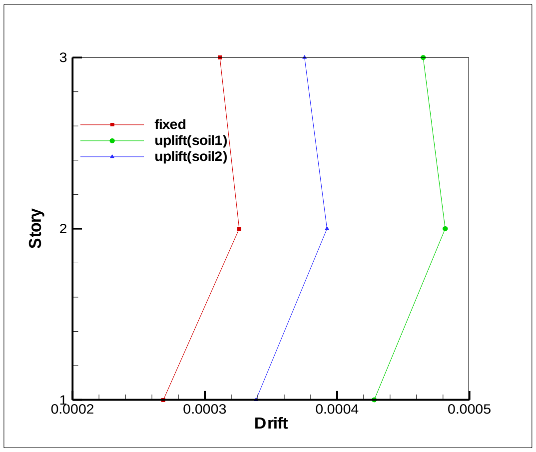

Figure 11 – Story drift ratio for three-story structure with CBF system

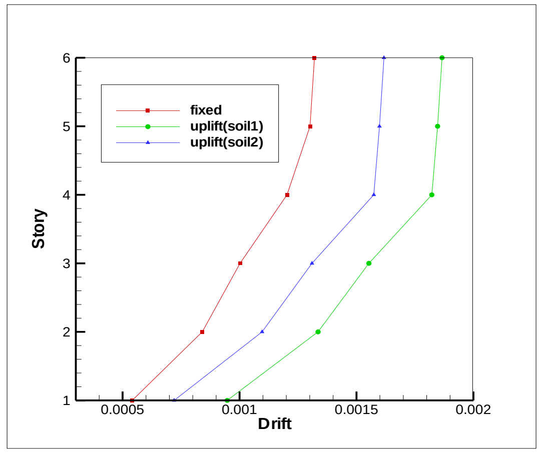

Figure 12 – Story drift ratio for six-story structure with chevron system

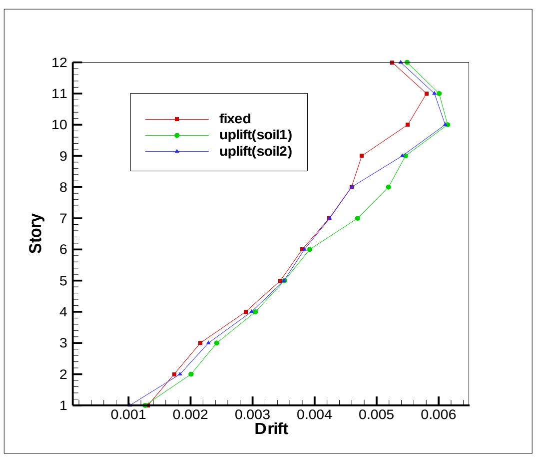

Figure 13 – Story drift ratio for twelve-story structure with EBF system

8. CONCLUSION

A summary of the results of this study may be presented as follows:

1. Comparison of rate of uplift for various structures showed that maximum uplift occurred in the part of foundation located on side axis of the structure. This part of foundation carries the brace's load too. It is also noted that with an increase in the height of structure the foundation uplift increases.

2. According to the analysis presented, it can be said that foundation uplift causes an increase in the structure's period. This increase is greater in the beginning vibration modes of the structure. The greatest increase in the period occurs for structures located on the soft soil. The increase in the period means a decrease in the rigidity of the structure.

3. A decrease of rigidity in structures allowed to foundation uplift, it is expected that the base shear for all structures will decrease. The increase or decrease of base shear force depends completely upon the number

of floors, soil hardness, and type of brace; such that in the three and six floor structures the base shear decrease and in the twelve floor structures it remains unchanged. Also, the value of base shear experiences a greater decrease on the soft soil and EBF systems.

4. Foundation uplift causes the greatest increase of story drift ratio. This can cause an overturn of the tall structures. The greatest story drift ratio increase occurs for the structures located on the soft soil.

5. Greatest changes in structural seismic response occurs when the foundation is allowed to uplift and is located on soft soil; and the harder the soil the less likely that the structure will uplift.

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