Structural Design

design issues for structural engineers

Effect of Lateral Soil Pressure on Underpinning

By Dan Eschenasy, P.E.

In New York City, there are over 100,000 masonry buildings that were erected prior to 1930. Typically these are three to six story unreinforced masonry (URM) bearing wall structures with wood floors and rubble foundations. As a consequence of the high number and density of these buildings, a high percentage of new developments occur adjoining an URM building. Excavating for deeper foundations of new buildings will require some type of underpinning. Although there are several methods available, New York City contractors seem to exclusively use strip (also called pin) underpinning.

In recent years, investigations of several incidents showed that some contractors were paying scant attention to some critical activities (e.g. jacking). In some cases, strip underpinning might have been extended far beyond the range of where it had produced relatively safe results.

About six years ago, the New York City (NYC) Buildings Department established a special unit to focus on excavation and underpinning. As a result, the number and gravity of incidents has declined substantially. While engineering input has increased, the question of what the most appropriate method of analysis should be has not yet been entirely solved by the engineering community.

To motivate the profession towards a more in depth engineering approach to underpinning, the upcoming version of the NYC Building Code will require consideration of the effect of the soil lateral pressure on the structure of the building being underpinned. Given the high sensitivity of URM walls to out of plane loads, it is important to pay full consideration to the possibility that the soil lateral pressure acting on the underpinning might be partially transferred to the walls above. Although sometimes difficult, it is even more imperative to determine the effect of these pressures when the existing structure was erected based only on code prescribed empirical methods that did not fully include concepts like load path or wind design. Some of the engineering arguments that form the basis of this specific code requirement were presented in the May 2011 issue of this magazine (*Cases of Failure of Unreinforced Brick Walls Due to Out-of-Plane Loads*). This article presents a more detailed discussion of the lateral loads.

Empirical Methods and Lateral Loads

As long as underpinning is required only to transfer vertical forces to a deeper soil level, one only needs to verify that the transfer system does not introduce any eccentricity or local overstress and that the removal of overburden does not alter the soil bearing capacity.

During the construction phase, strip underpinning functions as a soil retaining system as well, resisting pressures perpendicular to the wall. This dual function (support of vertical loads of the existing wall and support of lateral pressures developed as a consequence of the excavation) provides significant savings that probably explains the present ubiquity of the method.

Transfer of Lateral Loads to the Structure Above

The underpinning procedure requires jacking or shimming to ensure that the transfer of vertical forces occurs with minimal vertical displacement of the structure above. The jacking develops a high frictional resistance and, together with the subsequent grouting, produces a connection capable of transferring shear forces. Whether or not it is capable of transferring moments, the installation becomes continuous for shear loads. A load path is created. This continuity of foundation-underpin makes impossible the prevention of transfer of lateral loads to the structure above.

One can minimize the loads transferred by approaching the soil retention function of the underpinning as a sheeting problem. This involves tying back the underpinning with anchors. Similar to anchored sheeting jobs, the engineer is required to select the tieback, its pre-stressing level and its timing in the construction sequence.

Tie backs and horizontal shoring solutions are becoming common for deep underpinnings but are still rare for depths less than 6 feet. The analysis presented here concentrated on these lower ranges, since they are most common.

Neither the technical literature nor design practice provide good examples of engineering calculations that take into account the effect of lateral loads on existing structures. Many engineers consider such calculations unnecessary. They argue that the load or displacement transferred to the existing building is extremely small and gets dissipated in the system. For these engineers, the success of the operations requires merely conforming to some empirical principles of execution such as controlling the run of sandy soils, providing a carefully designed box for the approach pit, careful jacking of the pin, keeping water away from the pit, etc.

Sensitivity Analysis

Due to modeling uncertainties and the large variety of possible conditions, a sensitivity analysis was deemed the best approach. Sensitivity analysis is a methodology that evaluates how the uncertainty in the output of a model can be apportioned to

Dan Eschenasy, P.E. is the New York City Buildings Department Chief Structural Engineer. He is an Honorary Member of SEAoNY.

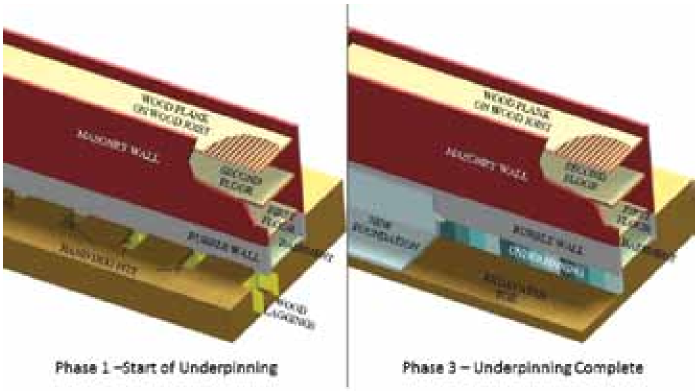

Figure 1: Phases of underpinning.

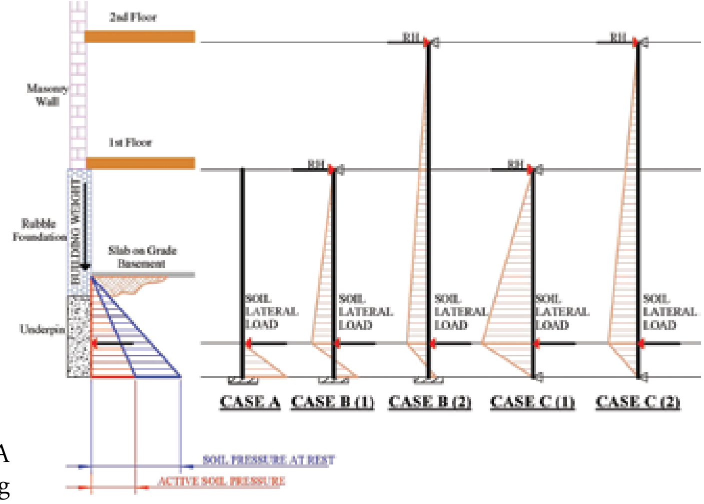

Figure 2: Structural models for underpinning Phase 3.

different sources of uncertainty in the model input. In this case the output is the magnitude of horizontal forces transferred to the existing structure. Some relevant results are presented here. Obviously, these results are for particular cases, and should not be used in calculations by others. It is also important to note that the lateral pressure on the underpinning results in unequal distribution of stresses on the underlying soil, concentrating stresses at the toe of the pin.

The scope of the analysis was limited to underpinnings less than 6 feet in height and installed under walls of tenements less than 6 stories. The changes in pin toe pressure are described in terms of ratio of final toe pressure vs. pre-underpinning pressure. The large distance between the building's shear walls restricting the out of plane movement of the bearing walls allowed us to neglect their direct effect on these bearing walls. In this simplified model, the lateral loads can be transferred to the underlying soil or horizontal diaphragms only. A rigid support at diaphragm level was assumed.

The analysis used models that follow the steps of the installation process. The various static models are shown in *Figure 2*. *Figures 3* to *6* depict the most relevant results, such as the theoretical effects on the underpin toe as well as the transfer of horizontal loads to the structure above. A typical underpinning procedure would be as follows (*Figure 1*):

Underpinning Phase 1

A sheeted approach pit is executed to allow digging under the existing foundation. The safe removal of earth from under the existing foundation is possible but also limited by the capacity of masonry (brick or rubble) to span several feet unsupported. After the pit under the foundation has reached the desired dimensions, a pin is poured. The top of the pin leaves a gap of several inches to the bottom of the existing foundation. The typical sequence of operation allows the simultaneous digging of several pits.

Underpinning Phase 2

Jacking or shimming takes place to control the transfer of vertical forces from the foundation to the pin. The individual pin installation is finalized by packing grout in the gap between its top surface and the bottom of the existing foundation.

Underpinning Phase 3

The underpinning is complete as pins cover the entire length of the foundation. No backfill or additional supporting structure have been placed on the excavated side. Several possible conditions of the attachment of the masonry wall to the floor diaphragm were analyzed (*Figure 2*).

Case A: There is no positive connection to the floors. The resisting friction forces are small. The base of the underpinning prevents rotation. The case when the joist/wall friction is sufficient to transfer the horizontal forces is treated at Case B (*see below*).

Case B: The base of the underpinning prevents rotation. Case B(1) corresponds to positive diaphragm (joist) anchorage to the wall occurs at the first floor. In some structures, the first wall diaphragm connection occurs only at the second floor since the first floor joists were simply placed on the shoulder offered by the rubble foundation. This situation is labeled as Case B(2).

Case C: The base of the underpin cannot prevent rotation. For Case C(1) the first positive diaphragm-to-wall connection occurs at the first floor. Case C(2) corresponds to a first positive joist connection occurring at the second floor.

Discussion and Findings

During Phase 1, per the analysis, some pins could overturn under lateral soil pressure. This analysis, also confirmed by the findings

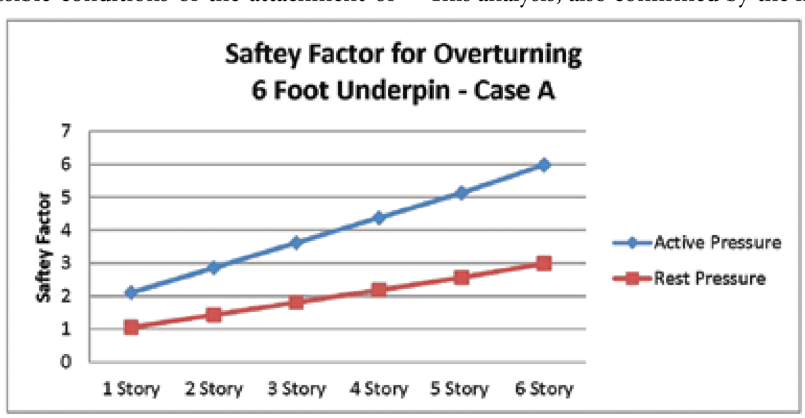

Figure 3: Variation of safety factor.

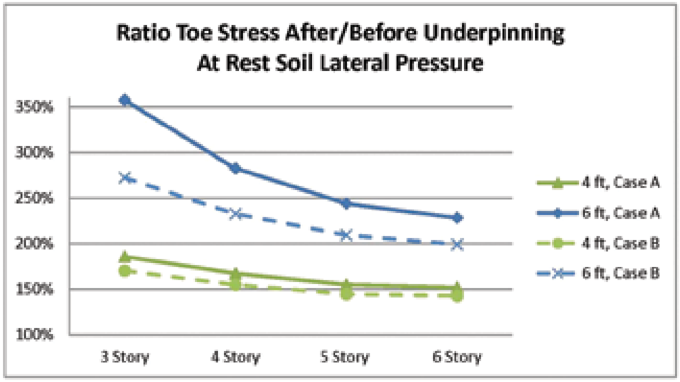

Figure 4: Variation in toe stress – at rest pressure.

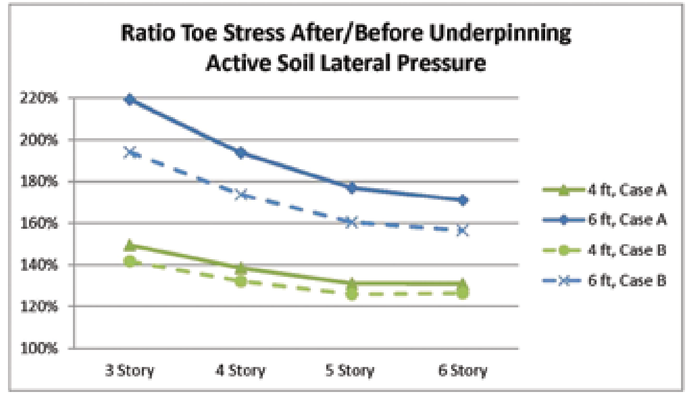

Figure 5: Variation in toe stress – active pressure.

of several incident investigations, clearly justifies the need to provide some system to counteract lateral pressures.

During Phase 2, jacking (or shimming) may result in an eccentric application of the load. The effects of various possible jack misalignments from the axis of the pin were evaluated. Misalignment from the center of the pin might increase the pin toe stresses by as much as 100%. Placing the jack perfectly at the middle of the pin avoids the application of a moment on the pin; but, since the position of the resultant of the existing vertical forces above is not exactly known, a misalignment might occur between the position of the jack and this resultant. As a consequence, some local stresses might double, but would probably be resolved within the masonry structure itself.

Both Phase 1 and Phase 2 are temporary. Most accidents during these phases can be attributed to contractor errors and, as such, is out of the scope of this study. Stresses and displacements present during Phase 3 are usually not temporary. The presence of a new basement wall on the excavated side will only limit further rotation or horizontal displacement of the underpinning, but will not eliminate the stresses already present.

For Case A, the analysis shows that under *at rest* soil pressure and depending upon the load of floors above and the pin height, the increase in stresses concentrating at the toe of the pin will reach 350% for a 6-foot underpinning (*Figure 4*). Case A occurs when no transfer is available (e.g. walls not anchored to diaphragm) or when the transfer path is damaged (e.g. end of wood floor diaphragm is rotten). The analysis also shows clearly that the lower the vertical load, the higher the possibility of overturning (*Figure 3*). In fact, in 2005 there were two collapses of one story buildings that were being underpinned.

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The modeling of Case B implies that as long as the soil bearing capacity is not exceeded, it will not influence the magnitude of horizontal forces transferred. Under at rest soil pressure, a 6-foot high underpinning will see a 200% increase in the stresses, concentrated at the toe. For this case, the horizontal load transferred to the building above seems to vary around 4 to 8% of the total lateral pressure. The load transferred to the first floor might exceed 50 pounds per linear foot, a relatively small but not to be neglected load (*see example in Figure 6*). Such load might be sufficient to break a deteriorating wall-to-diaphragm connection. Even though it would not drastically change the transfer of horizontal loads to the structure above, widening the pin towards the excavation side could significantly reduce the pressure on the soil. However, in NYC it is rarely possible to provide such enlargement.

In essence, Case C corresponds to a transfer of only vertical and shear forces to the soil (no moment restraint, rotation can occur). In Case C(1), the horizontal loads transferred to the first floor might exceed 200 pounds per linear foot (*see example in Figure 6*). For this case, the horizontal load transferred to the building above seems to vary around 15-25% of the total lateral pressure. If the wall-to-diaphragm ties at the first floor fail, the second floor diaphragm might be engaged. In this Case C(2), the horizontal load will diminish by about 40% compared with Case C(1). Case C requires verification of the capacity of the wall/foundation/underpin as a column under combined vertical and lateral forces. For Case C(2), the column might become too slender. For some Case C conditions, some overstressing tensile stresses might develop and the compressive stresses might approach the allowable compressive capacity of rubble walls (as it was listed in old codes). Crushing and/or bowing of rubble walls were observed in several cases. When the grouted pin-foundation connection is not able to transfer applied moments, the column structure (bearing wall plus underpinning) might become unstable.

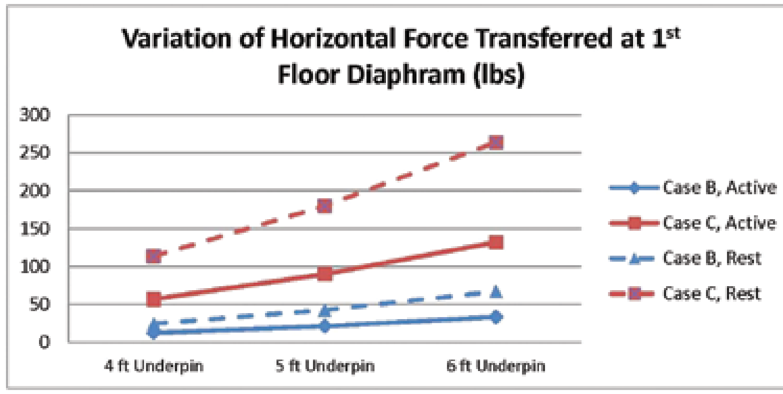

Figure 6: Horizontal force transferred at 1st floor diaphragm (example).

Old masonry buildings were never explicitly designed to sustain horizontal forces and, as a result, even smaller loads might crack or rake the structure. In some cases when interior plaster walls participate in the transfer of lateral forces, they might develop cracks. The author has repeatedly seen such events. Raking of walls is likely to introduce additional moments as it shifts the position of the resultant of the masonry weight.

Up to this point, the discussion of Case C and B involved only the *at rest* pressure that develops due to a stiff connection at the top of the wall. As noted, the size of the at rest lateral loads transferred to the structure might reach levels enough to rake the wall or develop relatively significant horizontal deflections. For certain soils, these movements could change the nature of the lateral pressure from at rest to active. As the active lateral pressure is smaller than the at rest pressure, its effects might result in moments that the soil underlying the toe of the pin would be more likely to sustain. Similarly, displacements and consequent active pressure can occur when the diaphragm does not provide a rigid support (e.g. deflects under load). The wall structure will be less stressed. But the reduction in lateral pressure can occur only subsequent to some larger deflections or raking, that is, after some possible damage has occurred to the structure. A structural engineer might be summoned only at this late stage, when he/she will be able only to determine whether the damaged structure has the ability to sustain the smaller lateral loads.

Conclusions

The sensitivity analysis was able to verify that the magnitude of the lateral forces transferred to the structure is dependent on the location and rigidity of the diaphragm, and on the capacity of the base of the underpinning to prevent rotation. The percentage of the total lateral force transferred to the building increases as the stresses at the bottom of the underpinning concentrate toward its toe, making rotation likely. The horizontal forces that develop can reach levels sufficient to damage the wall diaphragm connections and even rake some poorly built or deteriorating structures. These modes of damage match some of the distressed unreinforced masonry walls that were investigated following underpinning incidents.

The New York City Building Code's upcoming requirement of considering the effect of lateral forces on structures being underpinned seems fully justified. Underpinning might be more effectively designed by a collaboration of structural and geotechnical engineers.▪