POST-INSTALLATION PERFORMANCE OF ECCENTRIC SCREW PILE UNDERPINNING SYSTEMS FOR RESIDENTIAL FOUNDATIONS

Konstantin G. Ashkinadze, Consulting Engineer, Edmonton, AB, Canada, Ph. 780-945-9746, email@k-the-eng.com

ABSTRACT

The paper investigates post-installation performance of residential concrete foundation underpinning systems with helical (screw) piles, following claims by clients of two recent underpinning projects that the remedial work done "failed to stop the footing settlement and crack development" in their houses. Although screw pile-based underpinning systems have been extensively studied in recent years, most of the studies focused on the anchors and supporting brackets, not the "foundation" side of the underpinning arrangement. Two systems were considered: (i) the Rounded Corner Square Shaft (RCSS) system with 1.5" (38 mm) anchors installed at a 5° angle to vertical, and (ii) the Round Shaft (RS) system with 3.5″ (89 mm) diameter piles, installed with or without batter, cutting and not cutting off the projection of the strip footing at the location of the pile. As a result of finite element simulations, the performance of both systems, but especially the one where the footing overhang was not cut off, was found critically dependent on the available rotational restraint of the footing. If it is not sufficient, the anchors will exhibit post-installation deformation by bending and lateral movement of the pile shafts, which may cause continuing settlement of the supported foundation and reoccurrence of cracks in the interior finishes.

Keywords: Deformability, eccentric, foundation, helical pile, residential, screw pile, settlement, strength, underpinning.

INTRODUCTION

Underpinning with helical (screw) piles is one of the most popular technologies of repair of failed residential and commercial building foundations (Carville and Walton 1995). In many regions of North America, the native surface soils are prone to local subsidence due to changing weather conditions and groundwater regime, desiccation by tree roots, construction activities in the proximity of the foundation. Underpinning strives to resupport the existing foundation off deeper soil strata, unaffected by these factors. However, since the foundation is already in place, it is difficult to put the anchors directly underneath the footing. Rather, the anchors are installed at the side of the foundation and are connected to it by underpinning brackets (more frequently) or poured reinforced concrete caps. The steel brackets are more technological and are considered further in this paper.

Two underpinning systems, commonly used in the practice of underpinning residential foundations in Alberta, are investigated. The first system is a Rounded Corner Square Shaft (RCSS); the arrangement of the helical anchors and angular brackets is shown in Fig. 1. The piles are 1.5" (38 mm) square solid section with rounded corners, installed with a slight angle to vertical (a.k.a. batter). The projection of the strip footing is cut off at the pile location to reduce the eccentricity of the support.

The other system considered is a Round Shaft (RS) system using tubular anchors (3.5" OD × 0.25" thick pipe section; 89 mm OD × 6 mm in metric), which provides for heavier-duty underpinning. The current design of the bracket in this system only allows vertical installation and the footing overhang is not being cut off (Fig. 2). Notably the design procedure in this system does not account for the installation eccentricity in the anchor design other than the 3" (76 mm) pile installation tolerance.

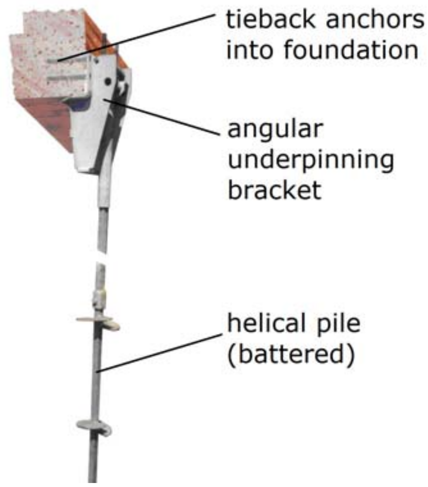

Fig. 1. Underpinning arrangement with battered piles and cut-off footing projection (RCSS).

Fig. 2. Underpinning arrangement with vertical piles without cutting off the footing projection (RS).

LITERATURE REVIEW

The behaviour of eccentric underpinning brackets for foundation walls and the resulting settlement of the footing has not been adequately researched. In a pioneering publication in this field, Seider (1993) emphasized the importance of keeping the eccentricities to a minimum, and suggested that the projection of the footing be cut off flush with the stem wall to attain a more concentric support. However, the underpinning diagram in his paper is as shown in Fig. 3. Seider mentioned that the existing foundation he was dealing with in his tests was sturdy with a massive footing. It was only used as a reaction block; the actual load was applied by a hydraulic jack at the centre of the bracket. Despite this limitation, his conclusion was that the moments developing in the stem of the anchor needed to be considered in the design. However, no attempt was made to evaluate the displacements of the anchor.

Subsequent publications on the subject (Hoyt et al. 1995, Youssef et al. 2006) placed the underpinning brackets at the edge of the footing for illustration only, without any analysis of the influence of such placement. In the tests by Youssef et al., the only eccentricity studied was the distance from the centre of the bracket bearing area to the centroid of the anchor. In actual underpinning projects, the line of action of

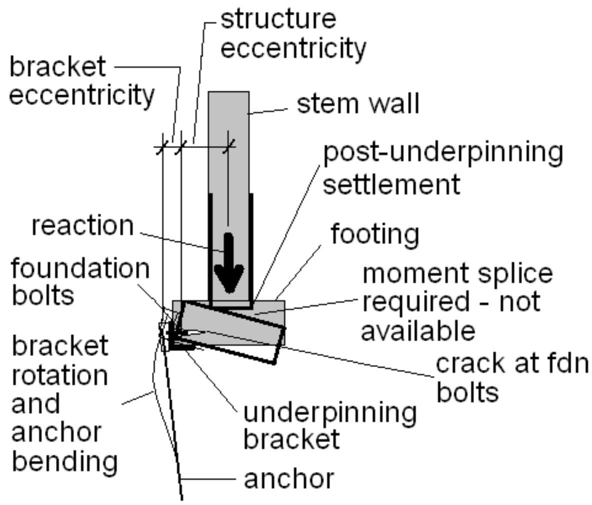

Fig. 3. Placement of underpinning bracket as per Seider (1993).

the vertical force is at the middle of the footing, not at the centre of the bracket. The resulting eccentricity will cause the footing to tip over the edge of the bracket (see Fig. 3).

The factors that could prevent this behaviour are (i) the moment resistance at the joint between the wall stem and the footing or (ii) the uplift resistance afforded by bolting the bracket to the foundation. However, in residential foundations, there is typically no reinforcement between the footing and the foundation wall, and the foundation bolts (if at all used) are installed into severely dilapidated concrete.

Perko (2009) developed detailed force transfer diagrams in an eccentric underpinning installation. His book, and the additional materials published at www.helicalpilebook.com, stress the need to minimize the eccentricity of the wall-to-pile connection by trimming the footing flush with the foundation wall. Preference is given to vertical piles and round shafts because of their greater lateral and buckling resistance. The installation batter is deemed structurally detrimental because it tends to pry off the underpinning bracket from the foundation. Its function is seen as enabling the contractor to avoid the roof overhang on a house when installing the pier, rather than adding any stability to the installed anchor.

Admitting that slender shafts of typical helical piles can support very little eccentric loading, Perko (www.helicalpilebook.com) proposed to treat the shaft as not taking any moment and apply the entire eccentric moment back onto the structure/foundation to ensure that the available lateral restraint is adequate to resist the induced overturning. If not, then the underpinning has to be done on both sides of the wall. However, no discussion of the resulting settlements of the underpinned foundation is provided.

The AC358 standard (ICC-ES 2012) resolves the rotational moments caused by load eccentricity into two components: bracket eccentricity and structure eccentricity (see Fig. 3). The duty of the underpinning system is only to resist the bracket eccentricity. The structure eccentricity shall be resisted by the internal strength of the structure to which the bracket is attached. Notably, Type A brackets (the eccentric ones applied from the side of the wall) are only shown in AC358 in the battered configuration. Also, the bracket is applied to the edge of the stem of the wall, not the edge of the footing overhang. Even so, AC358 stipulates that the eccentric brackets shall only be used to support structures that are braced as defined in 2012 IBC Section 1810.2.2 (ICC 2011). Location of eccentric anchors in a single line on one side of the wall only, whether battered or not, does not meet this requirement.

The problems existing here are illustrated by the following case studies from the author’s practice.

CASE STUDIES

–Case Study 1: Single-family residence, Edmonton, AB

The subject residence is a 4-level split, constructed in 1964. The house has developed cracks in the drywall finishes in the middle of the two-storey part and a vertical shifting crack in the crawl space at the location where it adjoins the garage foundation, as well as dropping of all the floors from front to rear to the extent of 2″ (50 mm). It was decided to underpin the entire rear wall and the portion of the side wall up to the large shifting crack at the junction to the garage.

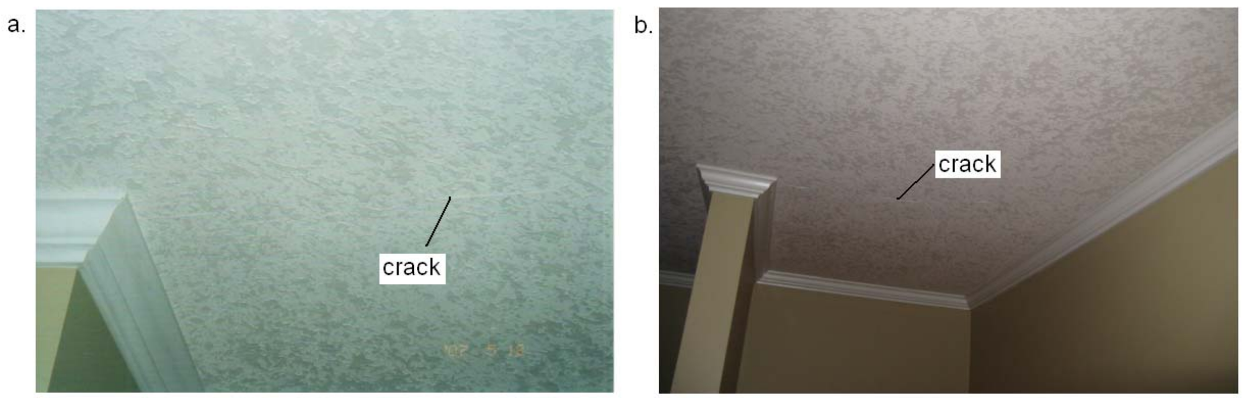

Fig. 4. Cracks in the finishes of the single-family residence (Case Study 1): a. – before underpinning, b. – after underpinning.

The underpinning work was completed in 2008. Ten (10) RCSS anchors have been installed, with a 5° batter to the depth of 18′ (5.5 m) from grade. The projection of the footing was cut off at the anchor location. The soil test performed on site showed high-plastic glaciolacustrine clay typical for Alberta. At the depths where the helices were placed, the soil was of firm consistency (SPT blow count 5 to 7 per 1 ft (0.3 m) of penetration, pocket penetrometer reading 1.5 to 2.5 ksf or 75 to 125 kPa).

In 2010, the owner contacted the engineer and the contractor again, claiming that the underpinning failed to stop the structural deformation and that the cracks in the interior finishes have reopened. The reinspection showed that some of the former cracks have reappeared, although to a smaller size (Fig. 4a, b). The likely reason for reoccurring settlement is bending of the anchor shaft due to the eccentric bearing. Footing settlements as little as 0.5″ (13 mm) are sufficient to cause the cracks to reopen.

–Case Study 2: Condominium building, Edmonton, AB

The subject condominium building (constructed in 1979) has three living floors and a crawl space basement. Its plan consists of two blocks of apartments separated by a central hallway. The foundation utilizes concrete walls 50″ (1.25 m) high for hallway walls and party walls resting on strip footings, bearing on top of clayey soil inside the crawl space. The soil did not have polyethylene cover, which led to its desiccation and fissuring. The building has developed extensive cracking over entry doors of the units on all three floors. The obvious problem was the foundation; large settlement-related inclined and horizontal cracks were found in the interior bearing walls through the entire length of the hallway. These walls were underpinned in 2009 with fifteen (15) RCSS anchors. The anchors were installed with a nominal batter to the depth of 29′ (8.8 m) below grade. The projection of the footing was cut off at the anchor location. The existing cracks in the foundation walls were epoxy-injected after the underpinning.

The condominium board contacted the engineer again over the Christmas holidays in 2013 with a complaint that the entry doors started to stick severely and new and larger cracks were appearing at the north end of the hallway. No problems had been experienced over the 4-year period until several days prior, when the outside temperature fell by 25°C in one day. The inspection showed that the suddenly increased heating demand caused a spray leak in a hot water manifold in the basement. The leaked water saturated the soil around the slender-shaft anchors and caused them to bend, which resulted in reopening of some of the previously closed and repaired cracks (Fig. 5). While this is not a situation normally considered in the design, the purpose of underpinning in the public opinion is to create a firm point of support off the deep soil strata, independent of what happens at the surface. Therefore, the underpinning system failed the expectations of the clients in this case.

Fig. 5. Reopening of previously epoxy-injected crack due to bending of anchors caused by upper soil saturation from a plumbing leak (Case Study 2).

NUMERICAL ANALYSIS

In search for clarity, a formal numerical analysis was undertaken using S-Frame finite element software (Softek 2009). The configurations considered were: (i) the RCSS anchor installed as in Fig. 1; (ii) the RS anchor installed as in Fig. 1; and (iii) the RS anchor installed as in Fig. 2. The footing was 18″ (460 mm) wide × 8″ (200 mm) thick, carrying an 8″ (200 mm) thick concrete wall, which is typical for residential foundation construction in Alberta. The anchor is 25′ (7.6 m) long, battered at 5°, with two helices, at 22′ (6.7 m) depth and at 25′ (7.6 m) depth, neglecting the pile tip. The projection of the footing in the configurations (i) and (ii) was cut off to within 0.5″ (13 mm) of the face of the wall.

Assigning the soil properties, in the vertical direction, a spring was introduced at each helix, calibrated to produce a 0.25″ (6 mm) total vertical displacement of the anchor under the design load. In the horizontal direction, a spring was applied at each node according to the formula by Davisson 1970 (CGS 2006):

$$k_i = 67\tau_u \times \Delta_i \qquad [1]$$

where τ_u = the undrained shear strength of the soil; Δ_i = the pitch of the nodes (1′ or 0.3 m). This formula is applicable to cohesive soils. The undrained shear strength of the soil was taken as 900 psf (45 kPa) for

Alberta firm clays prevalent in the Edmonton area. No vertical support from the soil to the footing was considered because of the perceived soil settlement. The only vertical support was from the anchor. In the lateral direction, loosening of the soil near the anchor at grade was considered, incidental to the process of the anchor installation. The subgrade modulus of the soil was varied linearly from zero at the surface to the maximum value, given by Eq. 1, at the depth of the disturbance horizon, taken as 2′ (0.6 m) for the RCSS anchor and 4′ (1.2 m) for the RS anchor, based on the author's field observations.

The working load on the anchor in the analysis was taken as 12.5 kips (55 kN), which was dictated by the hydraulic capacity of the portable pumping station used in the case installations described above. The load was uniformly distributed along a portion of the length of the bracket installed as in Fig. 1. The line of action of the force is shifted by 1″ (25 mm) outwards from the centerline of the wall stem because the load from the exterior wall in residences is applied closer to the outer face of the foundation, while the weight of the foundation itself is applied centrally. In reality, the load distribution along the length of the bracket bearing surface depends on the extent of contact available between the footing and the bracket. Fig. 6 illustrates the modelling of the bracket and pile top condition.

The frictional resistance of the concrete on the horizontal surface of the bracket is variable. If the structure eccentricity is small enough, the bearing stresses on the bracket will be positive and the moment due to the

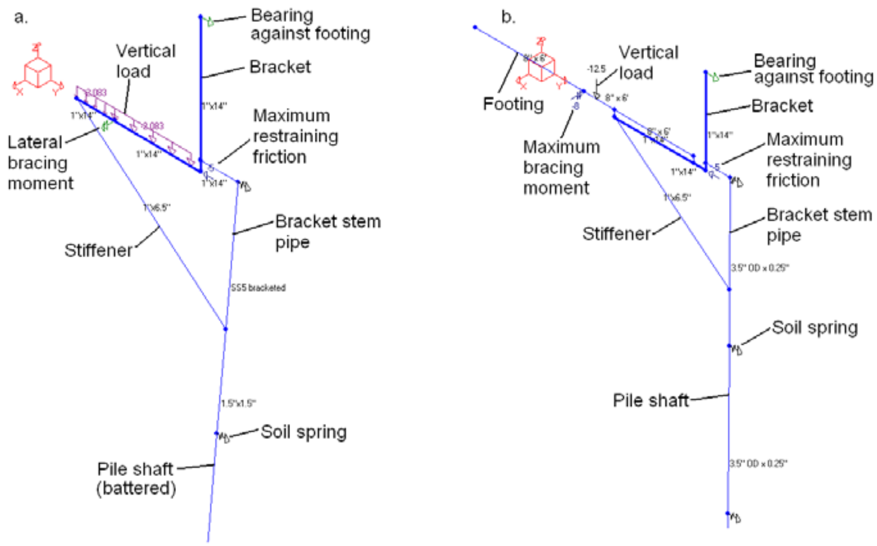

Fig. 6. Modelling of pile heads and brackets: a. – RCSS anchor installed as in Fig. 1, b. – RS anchor installed as in Fig. 2.

bracket eccentricity will be resisted as shown in free body diagram "b" in Fig. 14.4 of Perko (2009). Then, the bracket will be pushed down without rotation at the top. Otherwise, as shown in Fig. 3, the bracket and the footing will separate and the friction will not develop sufficiently to resist this moment. Both conditions are considered in the analysis below.

RESULTS

– First pass - no contact friction at the bracket

The first pass of analysis considered no friction at the bracket-footing interface. The resulting performance of the underpinned footing was not satisfactory. For the 1.5″ (38 mm) RCSS anchor installed as in Fig. 1, the footing settlement reached 0.45″ (11.4 mm) at the centerline of the wall stem and the moment in the anchor amounted to 3.28 kip-ft (4.45 kN-m), which exceeds the anchor allowable moment of 2.00 kip-ft (2.7 kN-m) determined as per the AISC Allowable Stress Design (ASD) steel design specification. For the 3.5″ (89 mm) diameter RS anchor in the Fig. 1 configuration, the settlement was smaller (0.36″ or 9.1 mm) but still considerable, and the moment in the pile (4.18 kip-ft or 5.7 kN-m) was just marginally less than the pile allowable moment of 4.36 kip-ft (5.9 kN-m) in the absence of compression. With consideration of compressive forces in the pile, the stresses in the shaft would also be excessive. Note that the loads applied were short of the listed allowable loads for these anchors. The patterns of anchor deformation and bending moment diagrams in the anchor are shown in Fig. 7 and 8.

– Second pass - with contact friction at the bracket

The second pass of analysis considered that friction would develop at the interface between the bracket and the footing. The resulting couple of horizontal forces can prevent the bracket from rotation, forcing it to settle with a straight back. However, the lateral force at the interface under the 12.5 kip (55 kN) vertical load cannot exceed 5 kip (22.2 kN), assuming the greatest achievable friction factor of 0.4.

The resulting performance of the underpinning system was marginally better but still not satisfactory. For the RCSS anchor installed as in Fig. 1, the footing settlement reached 0.385″ (9.8 mm) at the centerline of the wall stem. The maximum moment in the anchor was 1.77 kip-ft (2.4 kN-m). Together with the compressive forces, this moment produces excessive stresses in the pile shaft. For the RS anchor in the Fig. 1 configuration, the settlement was 0.33″ (8.4 mm) and the moment in the pile was 2.26 kip-ft or 3.1 kN-m. This is acceptable but again, it corresponds to the loads much below the listed allowable loads for these anchors and brackets.

For the RS anchors in the Fig. 2 configuration, a stable model could not be achieved within these terms, unless an external balancing moment is applied to prevent rotation of the foundation.

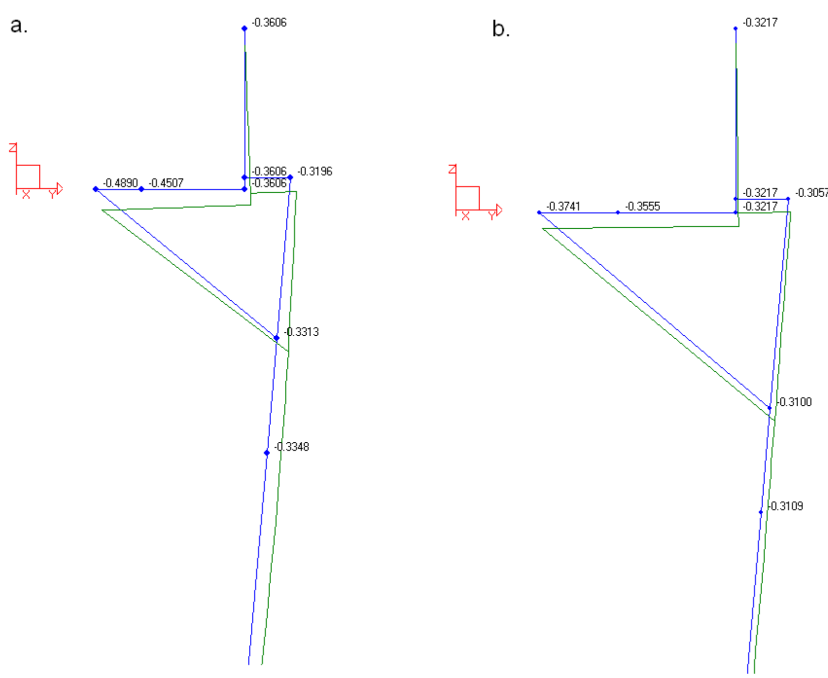

Fig. 7. Vertical displacements at the head of battered anchors – no friction at footing base (inches; 1 in = 25.4 mm): a. – RCSS anchor; b. – RS anchor.

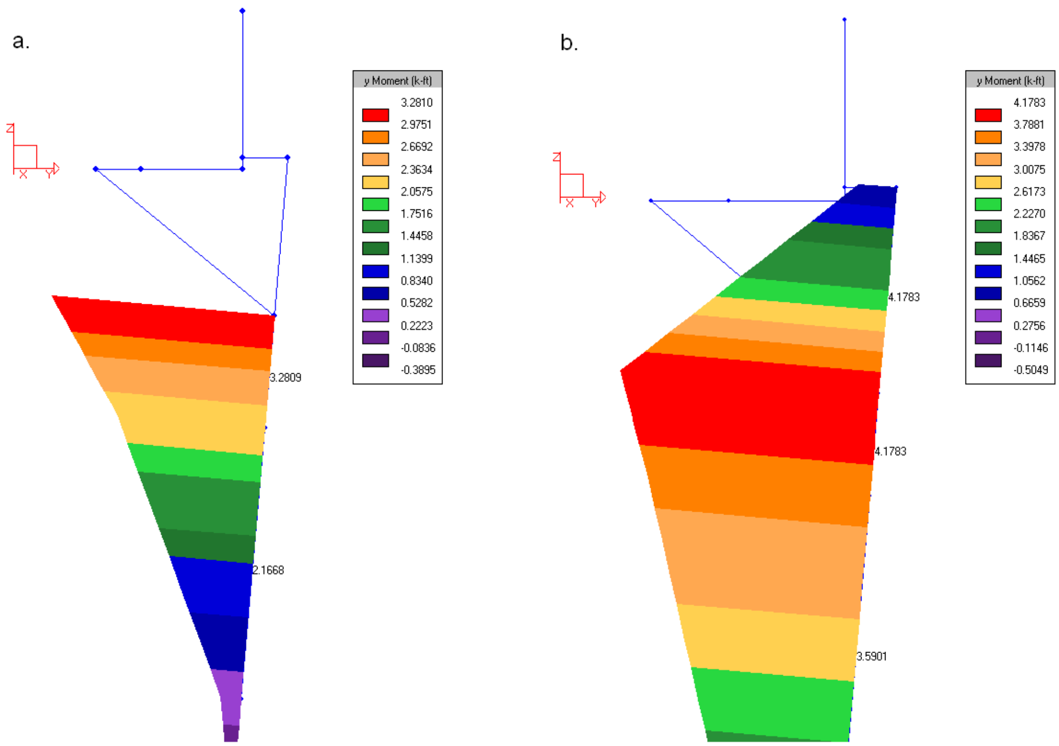

Fig. 8. Moments at the head of battered anchors – no friction at footing base (kip-ft; 1 kip-ft = 1.356 kN-m): a. – RCSS anchor; b. – RS anchor.

– Third pass – with external rotational restraint

In underpinning of a house or a building foundation, the additional balancing moment can be provided by torsional strength and stiffness of the foundation, restrained by intersecting walls at the corners. Perko (2009) provided recommendations for considering torsional resistance of a foundation underpinned from one side only. However, this is contingent on the foundation being intact and crack-free. Alternatively, the additional balancing moment can be provided by lateral bracing action of the main floor framing into the foundation wall. The following problems are envisioned with reliance on this factor:

– In most foundations requiring underpinning, there is a large tension-type horizontal crack in the foundation wall from prior soil settlement, which effectively ruins the bracing action;

– In many cases, there is no mechanical connection between the main floor and the foundation wall and the anchorage of the superstructure to the foundation is afforded by friction. In a typical bungalow, the maximum lateral force transferable through this connection is about 160 lb/ft (2.34 kN/m) and the maximum restraining moment per 1 pile that can be developed is about 8 kip-ft (10.85 kN-m);

– Settlement often occurs and underpinning is required in non-load-bearing walls that do not have floor joists framing into them but only end wall blocking. This arrangement has limited lateral resistance.

To model this effect, a rigid moment restraint was introduced at the central node of the footing, with the reactive moment limited to the above-noted capacity of the friction-governed lateral bracing connection. The results of the analyses with or without frictional restraint at the bottom of the footing are summarized in Tables 1 and 2, respectively. It is seen that the Fig. 2 configuration is the most dependent on the additional restraint. The two configurations with the footing projection cut off and the pile battered are more stable and less dependent on the overlying floor diaphragm. The pile moments in this variant are formally within the acceptable limits but in the absence of the frictional restraint, the pile strength utilization ratio reaches 74% under very moderate loads. For larger loads, shaft bending would cause the anchor to fail prematurely and/or develop excessive settlement. The lateral deflection of the anchor also increases sharply if the frictional restraint at the bottom of the footing is not available.

Table 1. Response of underpinning with rigid rotational restraint to the foundation, with friction at base.

Type of anchor	Δ vertical	Δ horizontal	M restraint	M pile
RCSS battered (Fig. 1)	0.32″ (8.1 mm)	0.023″ (0.58 mm)	3.0 k′ (4.0 kN-m)	0.24 k′ (0.33 kN-m)
RS battered (Fig. 1)	0.31″ (7.9 mm)	0.021″ (0.53 mm)	2.5 k′ (3.39 kN-m)	0.80 k′ (1.09 kN-m)
RS vertical (Fig. 2)	0.30″ (7.6 mm)	0.011″ (0.28 mm)	8.0 k′ (10.9 kN-m)	0.37 k′ (0.50 kN-m)

Table 2. Response of underpinning with rigid rotational restraint to the foundation, no friction at base.

Type of anchor	Δ vertical	Δ horizontal	M restraint	M pile
RCSS battered (Fig. 1)	0.335″ (8.5 mm)	0.060″ (1.53 mm)	5.26 k′ (7.13 kN-m)	0.53 k′ (0.72 kN-m)
RS battered (Fig. 1)	0.32″ (8.1 mm)	0.050″ (1.27 mm)	4.27 k′ (5.79 kN-m)	2.03 k′ (2.75 kN-m)
RS vertical (Fig. 2)	0.34″ (8.6 mm)	0.0784″ (2.0 mm)	8.0 k′ (10.9 kN-m)	2.29 k′ (3.1 kN-m)

CONCLUSIONS

The present study has shown that eccentric underpinning arrangements commonly used in the industry are insufficiently researched from the resulting foundation settlements' standpoint. The critical questions whether to cut off the projection of the footing, whether to batter the pile or to keep it vertical are still in ambiguity. The principal conclusion of the study is that the clients' expectation (fuelled by contractors' advertising) that "the footing will never settle again" may not be attainable in this eccentric bearing arrangement even if the anchors are designed and installed properly. A mere 0.5″ (13 mm) footing settlement may cause reopening of the cracks in the foundation walls and the living quarters' finishes. The reason is that the eccentric bearing of the underpinned foundation on the anchor brackets causes the pile shafts to bend and the foundations to tip over the edge of the bracket.

The total load eccentricity in an underpinning system consists of two components: bracket eccentricity and structure eccentricity. Conventional underpinning system designs only consider bracket eccentricity. Structure eccentricity is left to be resisted by the structure to which the bracket is attached. Difficulty to accurately reflect the existing bracing capability of the structure presents significant challenges in design.

The study has shown that the arrangement with a vertical pile and no cutting-off of the footing overhang is critically dependent on the extent of lateral restraint of the foundation wall by the overlying main floor and the friction developing at the base of the footing, and is inferior to the arrangements with battered pile and with cutting-off of the footing in the amount of the resulting footing settlement and pile forces. The arrangements with battered pile and cut-off projection of the footing also demonstrate the tendency to increased settlement and premature failure due to eccentricity of bearing, but they are less dependent on the available lateral restraint at the main floor level and are more tolerant of its imperfections.

Even the placement of the anchors on two sides of the wall may not resolve the problem, because each anchor will bend individually and still act as a soft spring support for the underpinned structure. The conclusion is not that helical piles should not be used to underpin houses, but rather that new systems of underpinning need to be developed to address these concerns.

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