RELEVELING AND BEHAVIOR OF STRAP RETROFITTED DAMAGED TEST FOUNDATIONS EXPOSED TO MINE SUBSIDENCE[1]

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Abstract. Test foundation walls were constructed in an area of planned subsidence. These crawl space-sized block bearing walls were located in the tension zone of a longwall panel. The test walls were 12.2 m (40 ft) long and were vertically loaded on top with soil bins to simulate the house weight. As the longwall proceeded past these test foundations subsidence movements damaged the test structures. Using a steel strap retrofit and applying a cementitious surface coating, the foundations were structurally and aesthetically repaired. The repaired test foundations underwent significant subsequent subsidence as an adjacent longwall was mined beneath. The response of the repaired foundation is summarized. The second part of the paper describes releveling another set of the damaged test foundations after the first subsidence event by using an innovative procedure. First the straps were applied to the block bearing walls and then with wall jacks the top of the walls were successfully made level. This releveling procedure is outlined with the results.

Additional Key Words: mine subsidence, foundation response, foundation leveling, foundation repair.

Introduction

In the first part of this paper, a field test of a newly developed technique for retrofitting residential foundation walls damaged by mine subsidence is described and discussed. There were three main objectives of the field test: 1. to evaluate the constructability of the new repair technique, 2. to investigate the performance of the retrofit under subsidence induced bending and climatic conditions, and 3. to relate the aesthetic and structural performance of the retrofit to factors such as subgrade bearing capacity, soil stiffness, angular distortion, and tilt. All results from all three objectives are discussed herein except for the influence of the subgrade characteristics on foundation behavior. Discussion of this latter topic would make this paper too lengthy.

The research described in the second part of this paper involved the field testing of an advanced tilt correction procedure that was proposed for houses tilted from mine subsidence (Marino, 1987). The objective of the field test was to determine: 1. the feasibility, 2. the constructability, 3. releveling capability, and 4. the level of difficulty of the proposed procedure.

Complete data summaries and analyses of the work reported herein can be found in Marino et al, 1992A; Marino et al, 1992 C; and Marino and Gamble, 1993.

Background and Site Conditions

The test site was located at a rural location just outside of West Frankfort, Illinois. At the test site a series of foundation walls were built by the University of Tennessee (Bennett, et al, 1992). Originally, the test walls were built to evaluate the effects of different foundation characteristics and subgrade materials on the structural response of similar foundations to mine subsidence movements.

The test walls were built with ordinary concrete blocks. These walls were not grouted nor reinforced. Block dimensions were 8" x 8" x 16". The

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walls were four courses high and 12.2 meters (40 ft) long. All of the walls ran side by side. Each wall was paired with another and supported soil-filled wooden bins which were used to simulate the load of a house (see Figure 1).

One pair of test walls was used for the retrofit test. They were designated as walls T5 and T6. Although the walls were of the same construction, different footing designs were used. The eastern-most foundation wall, T5, was founded on a footing constructed of normal concrete with a 0.004" plastic sheeting around it in an attempt to reduce friction between it and the subgrade. Foundation wall T6 was on a footing constructed of concrete with steel fibers in it. Figure 1 shows cross-section diagrams of the two footings.

The soil subgrade was a mottled brownish gray and orangish brown silty clay, CL, with trace to little fine sand. Hand penetrometer readings for the soil were consistently above 2.0 kg/cm^2 (4 tsf), so the silty clay is classified as being hard. Moisture content of the material was between 16 and 20 percent. Plastic indices for the clay ranged from about 24 to 36% with the natural moisture content from 5 to 10% greater than the plastic limit.

The walls were erected near two future longwall mine panels. Figure 2 shows the location of the north-south test walls in relation to the relevant longwall panels. The walls were built during the spring of 1990 before any subsidence took place. During mid-May of 1990 the face of the first longwall panel was beneath the test site. Significant damage in the walls was induced by the subsidence movement over that panel. Figure 3 shows the main cracking in both T5 and T6 as of May, 1991. The walls were repaired using the new strap technique between 5/13/91 and 5/17/91. The face of the second panel was adjacent to the test foundations in early to mid-June 1991.

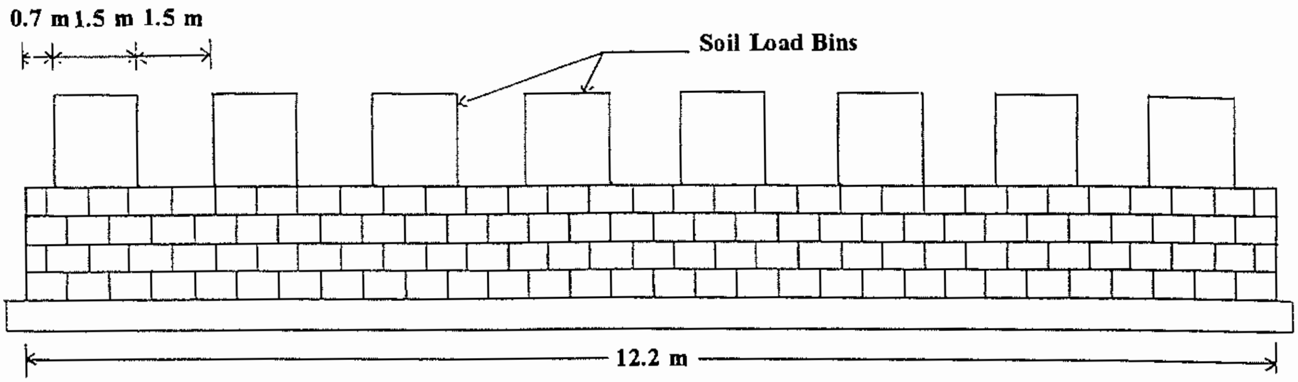
The tilt correction methodology was tested on the middle set of foundation walls (Numbers T3 and T4). These block walls were of the same construction as T5 and T6. The releveling of these walls was performed after the north panel was mined and the foundations were tilted 20-23 cm (8-9 in.) to the south with angular distortions of about 1/200.

Field Test of Foundation Retrofit Procedure

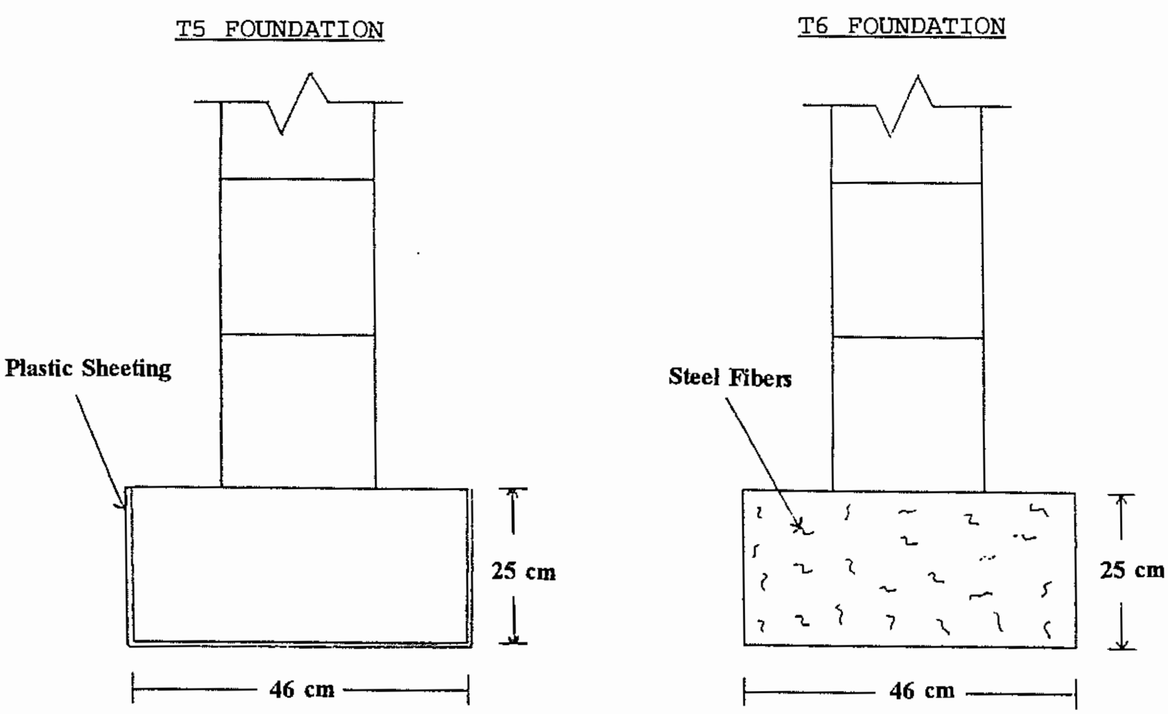
Overview of Wall Retrofit

The strap retrofit system used in the field test is illustrated in Figure 4. For test foundation T5, the strap retrofit was applied to both the east and west sides, and for T6 a strap was applied only to the east side. The total cross-sectional area of the steel was the same, however, for both walls. The purpose of attaching straps to both faces of wall T5, and only one face of wall T6 was to evaluate single strap performance and compare it to the performance of the wall with reinforcing straps on both faces. It was important to evaluate single strap performance, because if the larger single reinforcing straps perform adequately, the necessary reinforcement can be applied entirely to the interior wall faces. This procedure modification would be more cost efficient than applying straps to both sides especially where excavation would be required. Also note as shown on Figure 4, the amount of steel applied to the wall surfaces increased towards the middle of the walls. This increase in steel was calculated based on the increased bending moments estimated from the expected hogging-like subsidence movement resulting from when the southern panel is mined.

There were five main steps taken in retrofitting the damaged test foundations. First, the steel required for the repair was determined. Second, the first stage of repair was done and the walls were cleaned. This included filling open wall cracks in the expected zone of compression with mortar. By doing this large wall deflections due to crack closure were prevented. Shear strength was restored to the walls by grouting reinforcement into the cells of the concrete blocks in areas exhibiting diagonal shear cracks. Cleaning the walls was then completed, thus enabling the epoxy and fiber-cement to adhere to it. Third, the steel reinforcing straps were prepared for attachment. Fourth, the external reinforcing straps were attached to the walls to increase wall bending capacity. Fifth, a surface finish of fiber-cement was applied to the walls to improve the retrofit



ELEVATION



CROSS-SECTION

FIGURE 1 CONFIGURATION OF TEST WALLS

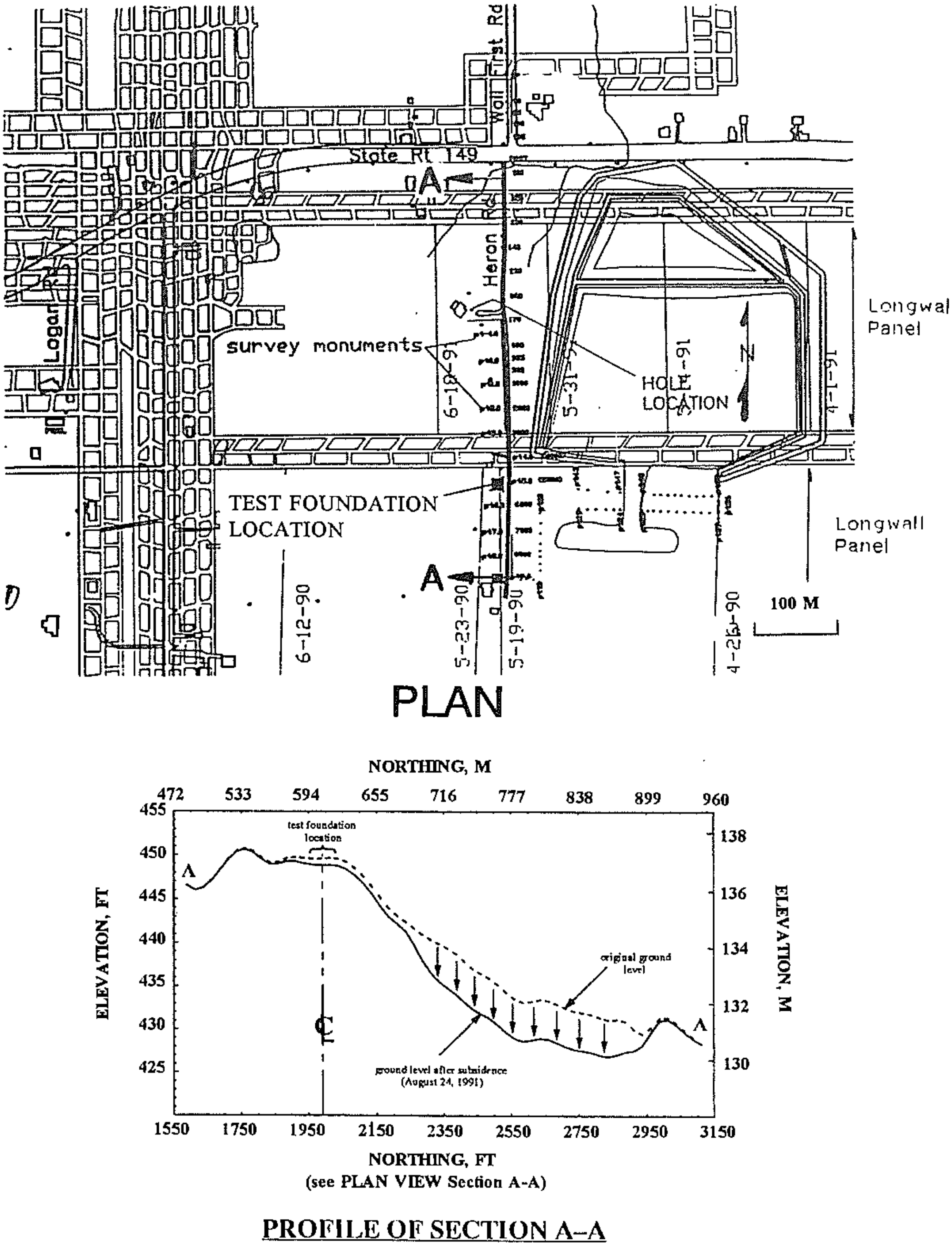


FIGURE 2 POSITION OF THE TEST FOUNDATIONS RELATIVE TO MINING ACTIVITY AND SUBSIDENCE PROFILE

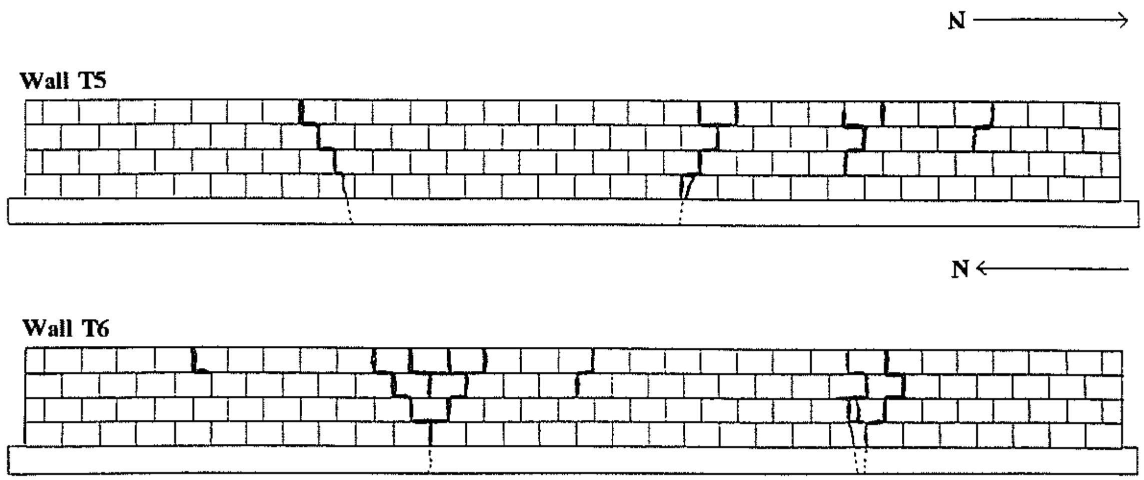


FIGURE 3 MAIN CRACKING IN FOUNDATION T5 AND T6 (MAY, 1991)

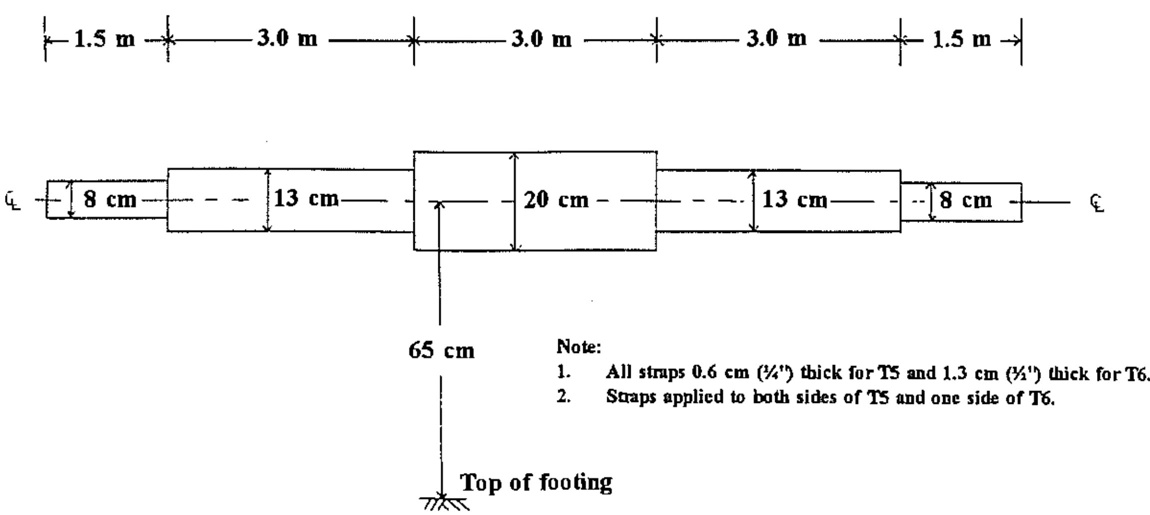


FIGURE 4 STEEL REINFORCING STRAP DIMENSIONS FOR WALLS T5 AND T6

appearance. A detailed description of the application of this strap retrofit process is given in Marino, 1992.

Instrumentation

A set of measurements was obtained periodically for one and one-half years after strap installation. This included: level survey of points on foundation walls, on wall footings, and on soil monuments along the foundations; continuous strain gauge measurements on the foundation walls along the straps and near the base of the retrofitted sides of the foundation walls; and relative vertical and horizontal displacements between the foundation wall and footing.

Consistent measurement procedures were maintained during the monitoring period. Strain measurements along the wall and footing and relative displacements between the same were performed using a Whittemore strain gauge. Details on the instrumentation and measurement specifications are given in Marino et al, 1992A and Marino and Gamble, 1993.

Response of the Retrofitted Foundation

Foundation Settlement

Based on the survey data taken during subsidence, the wall and footing settlement profiles for each retrofitted foundation are similar (even though steel was placed on only one side of T6 compared to both sides of T5). Furthermore, these profiles show the foundation walls and footings undergoing a more definitive hogging curvature with time. To demonstrate these points, foundation settlement measurements for T5 relative to the positions on 14 May 1991 are shown in Figures 5 and 6. Note only selective profiles are shown for clarity.

Using the ground and foundation profiles, the tilt and average angular distortion were calculated for three dates since the repairs were made. These calculated angular tilt and distortion values are compared in Tables 1 and 2 respectively. As can be seen in Table 1, the walls and footings for both foundations T5 and T6 have essentially tilted (or rotated) with the ground, reaching values of 0.48%. On the other hand, the angular distortion experienced by the repaired walls was typically less than that experienced by the footing and about one-half that of the soil at the severest levels (1/1200). Also, it is interesting to note that Wall T6, which has been strap retrofitted only on one side, appears to have bent less than Wall T5 with straps attached to both sides (i.e. 1/3,125 for T6 compared to 1/2,174 for T5).

Foundation Straining

Particle displacement diagrams along the straps and near the bottom of the retrofitted sides of foundation T5 and T6 were prepared and all showed similar trends. As examples of this data the particle displacement diagrams for the east face of foundation T5 at strap level and near the base of the foundation wall are depicted in Figure 7. The particle displacements were determined by adding the displacements measured between each set of Whittemore strain points starting from the north end of the foundation. Therefore, each point plotted, such as on Figure 7, shows the total of all point to point displacements measured south of Whittemore point in question.

As can be seen in Figure 7 little overall change in strain (as determined by the slope of the line) occurred between November 26, 1991 to November 29, 1992. Changes in the average longitudinal strain over this period of time ranged from about -2.0×10^{-5} to 3.0×10^{-5}. Even peak average strains during the entire test period were small and were 2.4×10^{-4} in tension and -4.8×10^{-5} in compression. Even though these strain values may appear low compared to the increase in the angular distortion (or deflection) of the walls (see Table 2), they are actually greater than values that would be predicted by the classical curvature-bending strain relationship (Popov, 1968) which is:

$$c = \epsilon / y$$

where: c = beam curvature
ϵ = longitudinal bending strain
y = vertical distance from neutral axis (assumed at bottom of footing)

The final strains measured in the wall are all tension, which is compatible with the wall being in the tension zone of the second subsidence event. However, the tensile strains at the bottom of the wall were larger than at the steel straps, 26 in. above the bottom of the wall on all three sides measured. This strain distribution corresponds to a case of sagging curvature in tension, while the measured vertical movements of the walls clearly indicate small hogging curvatures. The reasons for this inconsistency are not clear. A possibility for this inconsistency may be measurement error as the level of straining was low.

No comparison of foundation strain could be made with ground strain based on the soil monuments as these measurements were found to be not accurate.

Overall Performance

The November 1992 readings indicate the amount of ground distortion and tilt experienced by Foundations T5 and T6 since the repair was sufficient to cause damage to conventional residential construction. The most recent ground movements (shown in Tables 1 and 2) have been plotted on Figure 8. In Figure 8 are damage criteria for sag subsidence for houses resting on conventional block crawl-space foundations. This damage relationship assumes that ground distortion is empirically related to ground horizontal strain, i.e., as a house is exposed to some angular distortion level it is also exposed to a certain amount of ground strain. Therefore, ground strain can be considered to be inherently included in the damage plot shown in Figure 8.

As can be seen in Figure 8 a house exposed to the level of ground movement by the test foundations will likely sustain 10 to 40 percent Relative Repair Costs (RRC). RRC is defined as the percentage the necessary repair cost relative to the house replacement cost. This range of RRC values will usually include minor damage to the foundation and superstructure (see Table 3). At the most, possible replacement of accessory foundation element(s) or partial replacement of the brick veneer would be necessary. As noted above, the bending of the walls was about half that of the ground. This level of distortion reduces the estimated damage to Level I (see Figure 8). In other words, no damage to only RRC of 10 percent would be expected. Clearly then, based on this performance, these retrofitted test foundations are performing better than conventional construction since essentially only one minor discontinuous crack has appeared.

This crack is located about 9.40 m (370 in.) from the north end of Wall T6. The width of this crack has increased slightly over the last year of monitoring. This crack was more serious than the shrinkage cracks aesthetically, but is discontinuous and could probably be adequately covered with elastomeric paint if it were a problem. It should be noted, however, that this crack may close if the overall hogging curvatures in the wall become great enough with time as the crack originates at the base of the wall.

Aesthetic performance can be defined as the ability of the fiber-cement (Quikwall) coating to maintain an aesthetic appeal. Deterioration of the aesthetics of the surface cement is considered to occur when the propagation of cracks are visible to the naked eye at a distance of a few feet. The cracks may be load induced or the result of temperature, application, and curing.

Shrinkage cracks form when the fiber-cement coat contracts from drying or lower temperatures. Also, crazing or map-type cracks can occur depending upon the way the cement is applied. This type of cracking was found on all three retrofit faces and has not changed with time. These cracks could only be found through close observation. Therefore, none of the shrinkage cracking that occurred was considered to be an aesthetic failure. Figure 9 contains a photograph of the face of the fiber-cement on November 29, 1992.

Field Test of Tilt Correction Procedure

General Procedure for Releveling

For a tilted and damaged foundation in the tension zone, straps are attached with epoxy to the upper part of the foundation wall (see Figure 10). Before straps are installed, however, any necessary treatment to existing cracks or shear reinforcement to this upper wall section must be completed. Jacks are then installed in windows made in the wall below the

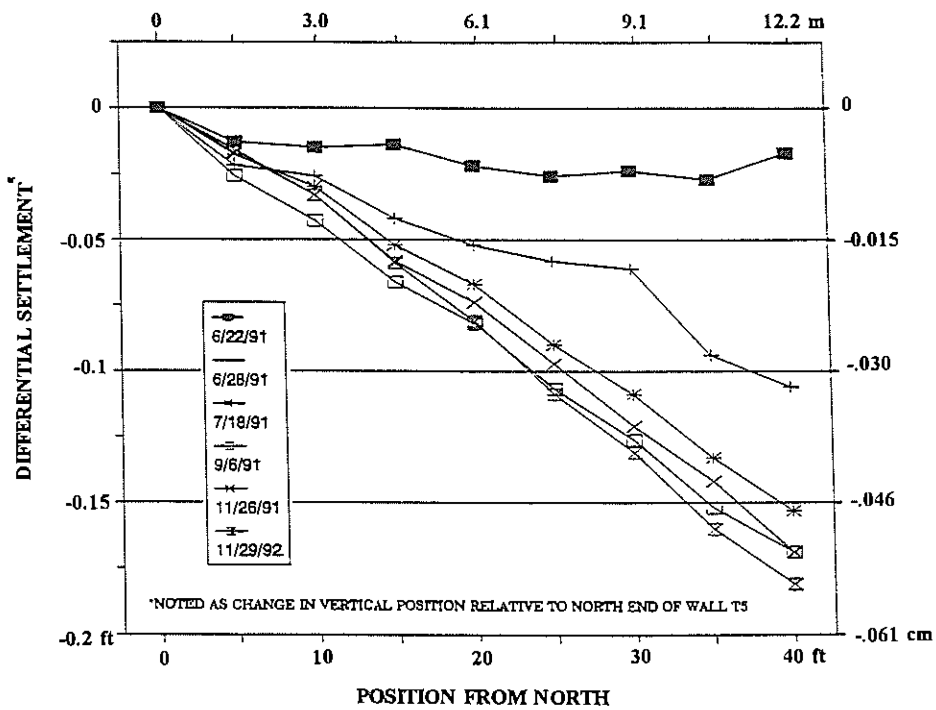


FIGURE 5 DIFFERENTIAL SETTLEMENT OF RETROFITTED WALL OF FOUNDATION T5

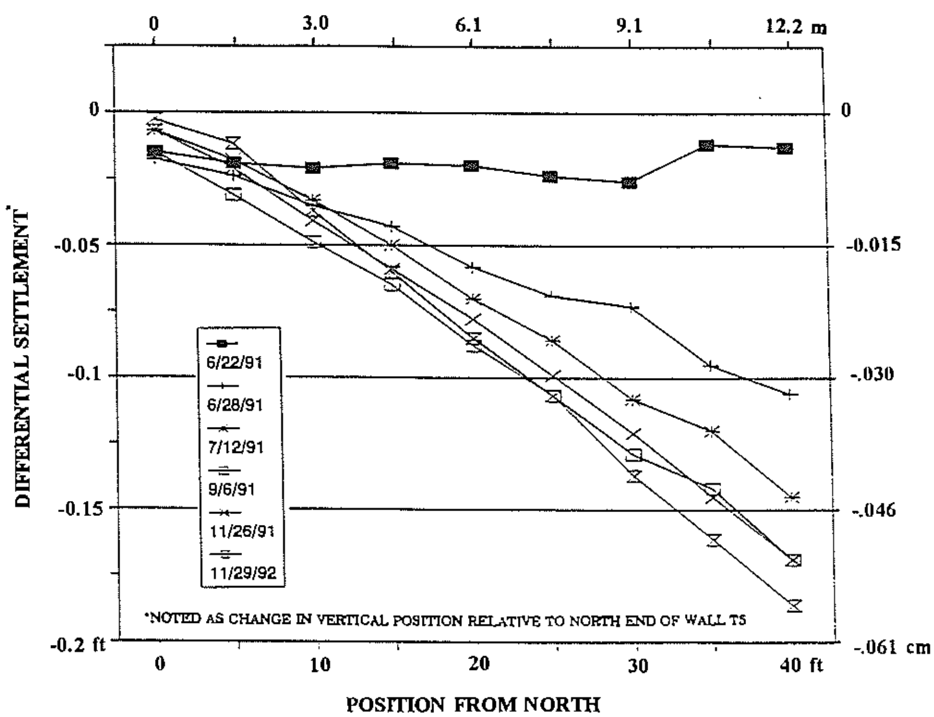
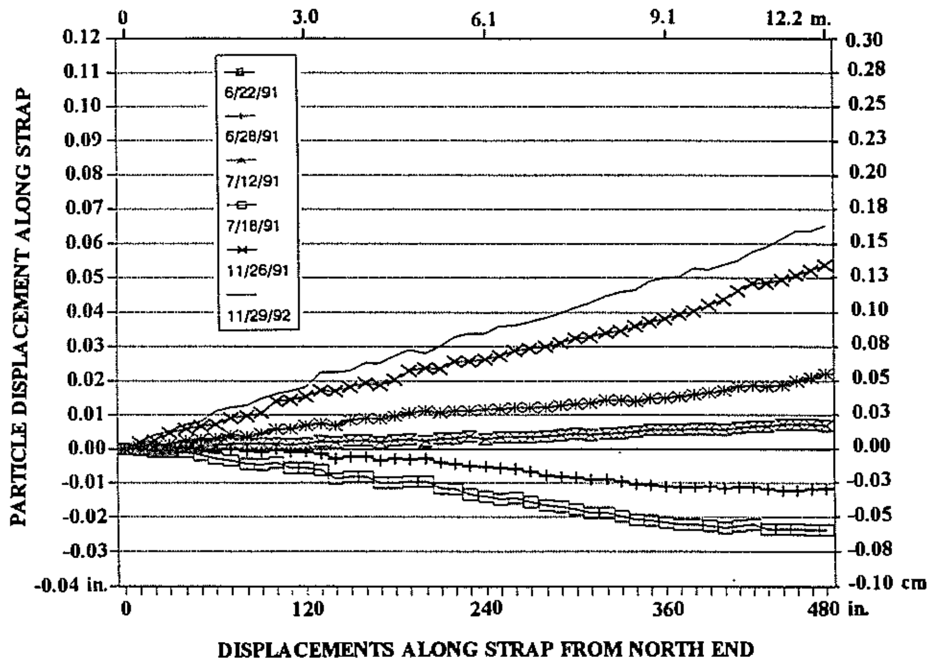


FIGURE 6 DIFFERENTIAL SETTLEMENT OF FOOTING OF FOUNDATION T5



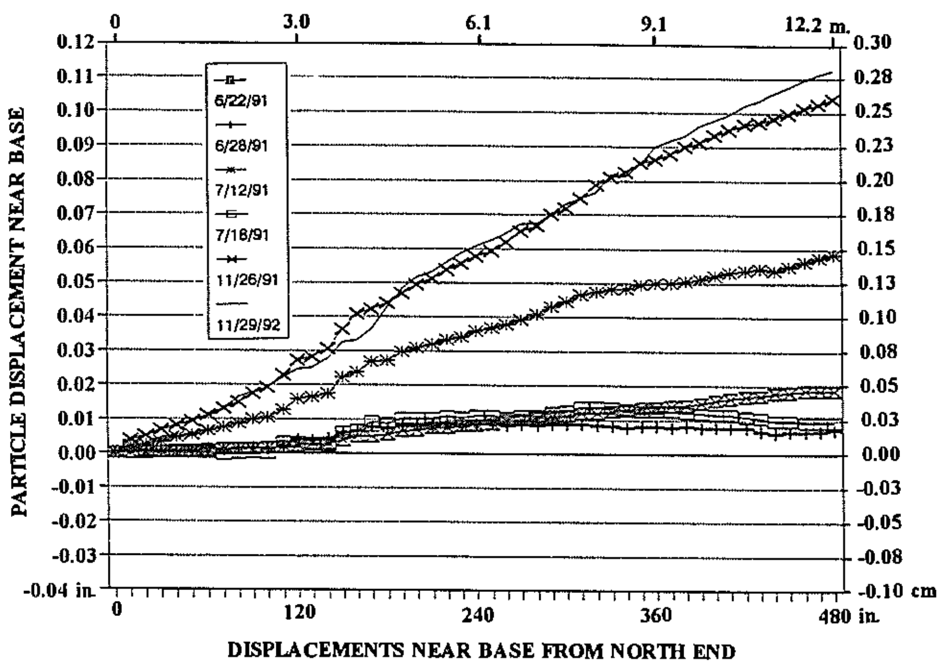


FIGURE 7 RELATIVE PARTICLE DISPLACEMENTS ALONG EAST FACE OF RETROFITTED WALL OF FOUNDATION T5

TABLE 1 TILT COMPARISON*

T5	7-12-91	11-26-91	11-29-92
Retrofitted Wall	0.37%	0.43%	0.45%
Footing	0.35%	0.40%	0.46%
T6			
Retrofitted Wall	0.36%	0.47%	0.48%
Footing	0.36%	0.43%	0.46%
Soil	0.39%	0.44%	0.48%

* Average tilt computed over entire length of profile since 5-30-91

TABLE 2 ANGULAR DISTORTION COMPARISON*

T5	7-12-91	11-26-91	11-29-92
Retrofitted Wall	roughly straight	1/2,500	1/2,174
Footing	straight	1/2,206	1/6,250**
T6			
Retrofitted Wall	straight	1/6,250	1/3,125
Footing	1/1,667	1/2,500**	1/1,500
Soil	1/1,667	1/1,282	1/1,210

* Measurement taken over entire soil monument profile (i.e., middle 30 ft), and includes angular distortion since 5-30-91.

** Possibly low value due to an erratic point.

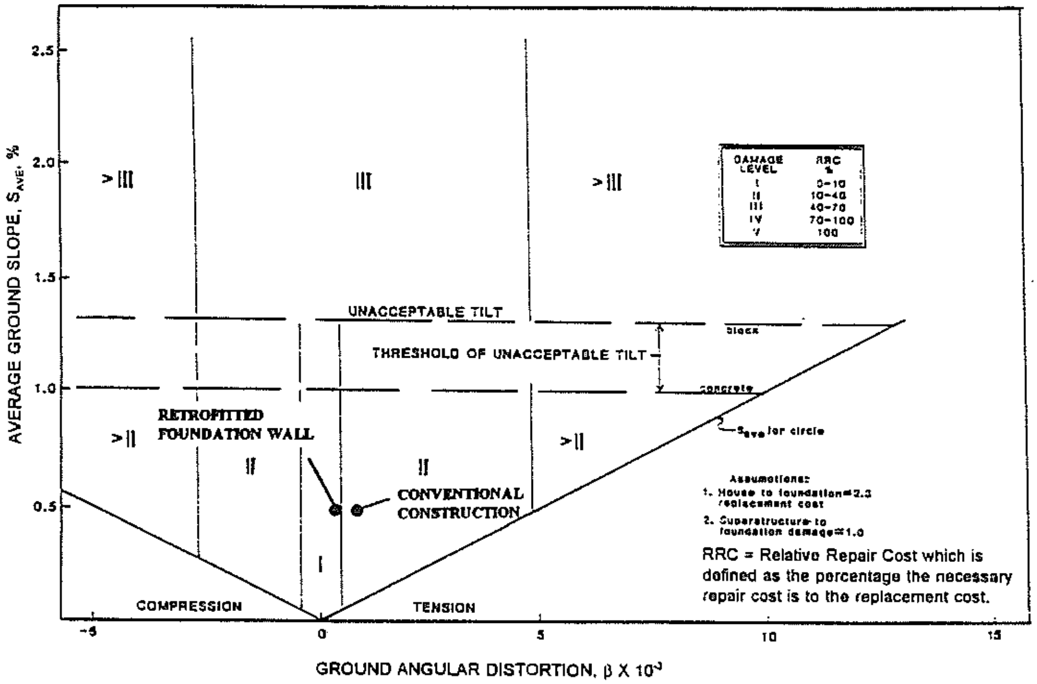


FIGURE 8 DAMAGE LEVELS RELATED TO THE ASSOCIATED ANGULAR DISTORTION AND AVERAGE SLOPE OF THE SAG PROFILES FOR HOUSES ON CRAWL-SPACE FOUNDATION (Marino and Mahar, 1985)

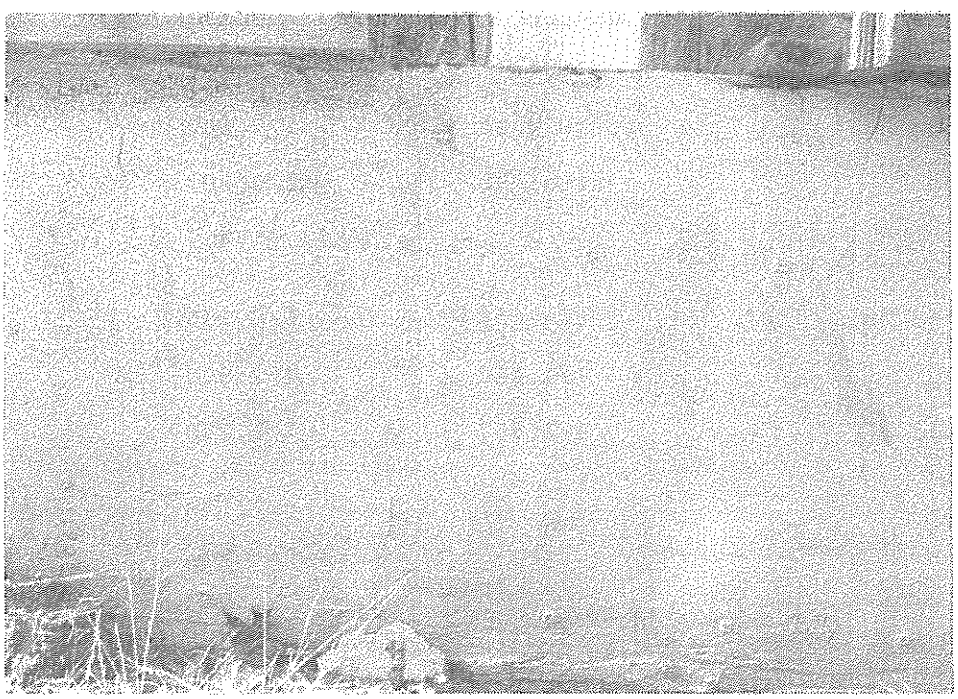


FIGURE 9 PHOTOGRAPH OF FACE OF FIBER-CEMENT COATING ON NOVEMBER 29, 1992

TABLE 3 COMMON SUBSIDENCE REPAIRS FOR HOMES WITH CRAWL SPACES AT DIFFERENT LEVELS OF DAMAGE (Marino and Mahar, 1985)

DAMAGE LEVEL	RRC	COMMON REPAIRS FOR CLASS B HOMES† FOUNDATION	EXTERIOR	INTERIOR
I	≀ 0.1	Patching of minor wall cracks.	Tuck pointing of cracks in brickwork. Possible trimwork of siding/paneling. Repair of molding, and caulking separations. Possible repair of spout-roof separations.	Patching of minor wall cracks and painting of the dry or plaster walls in typically less than half the inside. Racked openings.
II	0.1 - 0.2	Same, possible replacement of accessory foundation element(s) (e.g.; displaced/cracked isolated block crawl-space section, slab foundation, exterior concrete, etc.)	Same.	Same, but with generally larger cracks and possibly paint entire inside. Repair caulk separations around fixtures and openings.
	0.2 - 0.4	Same.	Same, with possibly some replacement of brick.	Same.
III*	0.4 - 0.55	Same, replacement of crawl-space or crawl-space with a small basement section. House jacking necessary. Redecoration of living areas on a slab.	Same, but also partial replacement of siding, replacement of masonry veneer panel (less than one side and one story).	Same.
	0.55 - 0.7	Same.	Same, but replacement of 1 story brick veneer.	Same.
IV*	0.7 - 1.0	Same.	Same, replacement of exterior on wall or roofing. Repair of cracking in chimney-fireplace.	Same.
V*	1.0	REMOVE AND REPLACE HOUSE.		

† A class B home has a masonry crawl-space foundation, with possibly a small basement section. The house is wood-framed with brick, paneled, and sided exterior(s) and can have an attached garage.

The term "same" refers to damage conditions which are present at a lower level and have not been superseded by a worse condition.

* Possible abatement measures necessary.

strapped portion. The jacks are used to lift and level the upper part of the foundation and house. The jacking either occurs directly below a common mortar joint if the foundation is block, or a cut is made parallel and below the strap if the wall is concrete. During jacking a gap in the wall is created and is extensively and continually shimmed to prevent the occurrence of dangerous out-of-plane eccentricities, and to protect against the effects of loss of support due to hydraulic jack leaks.

Once the house and the upper strapped section are level the gap created in the wall can be filled with mortar or concrete and any treatment required for existing cracks can be taken care of. After the foundation walls are completely retrofitted and the house is level, the walls can be covered with fiber-cement for mainly aesthetic purposes. Of course, interior beams and/or walls are also appropriately lifted during the jacking process.

Wall Preparation for Jacking

Structural preparation similar to that conducted on Foundation T5/T6 was performed on T3/T4. (Note here, however, vertical steel straps were used in lieu of grouted-in rebar for shear strength repair. This was the first attempt at using vertical straps on the walls for shear strength repair.) Windows for the jacks were knocked out in the lower course of block at the prescribed places along the walls (see Figure 10). Bottle jacks were then inserted in the windows (see Figure 11).

Because the test foundations to be lifted are essentially two-dimensional structures interior bracing was felt necessary to provide some lateral support. The wood bracing system was designed to allow the jacked part of the foundation to move only in a vertical plane.

Instrumentation

In order to evaluate the amount of lift imposed on the strapped wall sections and soil bins, and to assess the induced strains in the steel straps, survey control points and Whittemore gauge points were established before any jacking was done. The survey control points were set on the top of the wall and were spaced about every 1.5 m (5 ft). Whittemore points were also located on the straps where maximum tensile strains were expected during the jacking process.

Jacking Process and Performance

The jacking process was conducted in three stages: 1. uniformly lifting walls 2.5 cm (1 in.); 2. rotating walls to level positions; and 3. adjusting jacks to straighten the top of the walls (see Figures 11 to 13). The main purpose of Stage 1 was to provide sufficient separation as to allow the north ends of the walls to rotate as the lower south ends were jacked upwards.

It was found during the Stage 2 of the jacking, the test foundation could be lifted 2.3 cm (0.9 in.) without causing excessive strain in the steel (a maximum strain of 0.00022 was measured at 2.3 cm jack displacement). Therefore, 2.3 cm was used as the maximum lift criterion. During Stages 2 and 3 the lifting was monitored mostly by measuring induced separation of the mortar joints with only occasional level surveys. Also when jacking, the surveying effort was lessened because negligible foundation settlement seemed to occur during jacking. Once Stage 2 was thought complete a survey was taken. Jacks were adjusted accordingly to bring the foundation walls level end-to-end. In order to bring the walls level they had to be lifted as much as 20-23 cm (8-9 in.) at the south end.

Although the walls were level end-to-end it was discovered that the middle of the walls were about 3.8 cm (1.5 in.) higher. This was determined by stretching strings from one end to the other at the tops of the walls. The tops of the walls were then straightened out by adjusting the jacks until both strings were coincident with the tops of the walls (see Figure 13). With the walls now straight the jacking was complete. The induced mortar joint separations were supported with additional shims and the jacks were removed.

After all the jacking was complete and the walls were straight and level, the most stressed point measured in the steel (based on Whittemore gauge measurements) reached only about 20 percent of its yield strength.

FIGURE 10 ALL JACK WINDOWS KNOCKED OUT

FIGURE 11 JACKS INSERTED IN WINDOWS

FIGURE 12 JACK ELEVATED IN WINDOW BY THE USE OF PLYWOOD PLATES

FIGURE 13 FINAL JACKED POSITION OF WALL

Summary and Conclusions

In 1987, new, more cost-effective methods of retrofitting damage foundations and tilt correction to sloped house foundations were proposed. The application of this retrofit technique is described herein and involves a method where steel straps are attached to foundation bearing walls. The advanced tilt correction methodology, also described in the paper, basically consists of: 1. reinforcing the upper section of the foundation walls using the advanced strap reinforcement technique; 2. inserting jacks in windows cut in the walls immediately below reinforced sections; 3. incrementally jacking level the reinforced wall sections and house; and 4. backfilling the separation created by lifting the reinforced section off the remainder of the foundation with mortar/concrete.

In this paper a field test of the proposed repair technique for retrofitting residential foundation walls damaged by mine subsidence is described and evaluated. The retrofit technique was designed to be cost efficient, simple to build, effective in strengthening foundation walls, and crack resistant. The method used consists of repairing wall cracks, externally reinforcing the walls, and covering the walls with a crack resistant aesthetically pleasing fiber-cement coating. The field test was located at a rural location just outside of West Frankfort, Illinois. Four block high, forty-foot long block walls, resting on strip footings were used in the test. These walls were located over a longwall coal mine.

The retrofit was simple to construct using only current methodology and was cost-effective in resisting the subsequent ground movements.

Over the monitoring period of 1.5 years, the hogging curvature of the ground had increased slightly to an angular distortion of 1/1,210. The angular distortion of the retrofitted foundation walls were about one-half that of the adjacent ground. Only slight changes in longitudinal strain have occurred over the monitoring period. Both the two-strap and one-strap foundation walls, T5 and T6 respectively, performed well. Also, the fiber-cement finishes have retained their aesthetic appeal after one and one-half years of weathering.

This proposed method of tilt correction was successfully and quite easily applied to relevel two field test foundations near West Frankfort, IL. These foundation walls were jacked up differentially about 20-23 cm (8-9 in.) In addition to jacking the walls level, it was also possible to eliminate the hogging in the wall. The wall slopes and deformations were caused by longwall mining activity. After all the jacking was complete and the walls were straight and level, the most stressed point in the steel reached about 20% of its yield strength, thus leaving adequate capacity to resist residual subsidence movements. In fact, it was found that the upper wall could be lifted about an inch at one jack without stressing the steel excessively.

Acknowledgements

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