# MONITORING OF A HOUSE DURING MINING SUBSIDENCE

G. Lin[1], E.C. Drumm[2], R.M. Bennett[2], L. Powell[3]

Abstract: The structural response and subsequent damage to a residential house were monitored during an active longwall mining operation. The monitoring program consisted of survey monuments on the ground surface around the house and at various locations on the structure. Structural tilt, soil strain and soil pressures were also recorded. The structure was subjected to a cyclic loading consisting of initial tension, then compression, followed by a second tension in the ground surface. The unreinforced foundation experienced extensive cracking and was left with permanent displacements. Although the structure experienced significant shear and tilt during the subsidence, it was left with only minimal damage. The observations suggest that structures in subsidence-prone areas must be able to withstand significant angular distortions, especially during the initial tensile phase of the ground deformation. Current construction practices can be modified to induce composite action between the foundation and superstructure and thus improve the resistance to subsidence-induced ground movements.

Additional Key Words: subsidence, structural damage, foundation damage

## Introduction

With the growth in demand for coal, and the resulting increase in coal production, underground mining will be performed under existing structures. In addition, new structures will be built over areas that were mined previously. Mining induced ground subsidence is estimated to result in damage to residential structures costing between 25 and 35 million dollars each year. This damage is estimated to exceed $1 billion over the final quarter of this century (Gray 1988).

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New construction procedures and techniques are needed to reduce structural damage due to mining induced ground movements. However, the structural response to ground movements is very complex due to interaction effects between the ground, foundation and superstructure. It is essential to understand these interaction mechanisms for the development of new damage mitigation procedures.

Although the subsidence above abandoned room-and-pillar mines is very unpredictable, the ground subsidence induced by a longwall mining is generally predictable both in terms of magnitude and timing. As such, longwall mining subsidence provides a unique opportunity to investigate structural response to subsidence.

A one-story ranch-type house in southern Illinois was monitored during longwall mining subsidence. The monitoring program consisted of survey monuments on the ground surface around the house and at various locations on the structure. Structural tilt, soil strain and soil pressures were also recorded. This paper presents some results from the monitoring program and discusses the interaction process between the ground, foundation and

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superstructure. Some recommendations are provided in terms of inexpensive modifications to current construction procedures to minimize structural damage during mining induced ground subsidence.

## Site and Structure Background Information

### Structure

The house was a one-story wood framed ranch-type house constructed over a crawl space. The house has a concrete slab porch at the front and an annex on the back. The main structure has a plan dimension of about 17 m long and 8 m wide. The floor plan and elevation are shown in Figures 1 and 2, respectively. The walls were composed of fiber board and wooden siding over wooden studs. The interior walls were covered with gypsum wallboard. The house appeared to be in relatively good condition prior to the mining subsidence.

The main structure was supported on continuous unreinforced concrete strip footings about 0.6 m wide as shown in Figure 3. Although the footings along the four sides were connected at the corners, they were not at the same elevation. The footings at the south and west sides were poured approximately 20 cm higher than the footings at the north and east sides. A wooden beam, consisting of three nominal 50 by 200 mm boards, ran longitudinally down the center of the house. The beam was supported on six evenly spaced isolated concrete footings of approximately 0.6 m square. Wood joists spanned between the top of the foundation and the main beam. The house was anchored to the foundation with 9 mm L-shaped anchor bolts at 2 m on center. The sill was a 50 mm by 150 mm board with 18 mm holes for the anchor bolts. There was evidence of some rot in the sill.

### Site Conditions and Mining Operations

A borehole was drilled to investigate the subsurface materials above the mine seam. It was found that the overburden consisted primarily of shale and siltstone, with some interbedded sandstone and three thin coal seams (Mehnert et al. 1992). The surface soils were loess deposits consisting primarily of low plasticity silts and clay. The soil layer was approximately 7 m thick with the soil having a plasticity index of 10, angle of internal friction

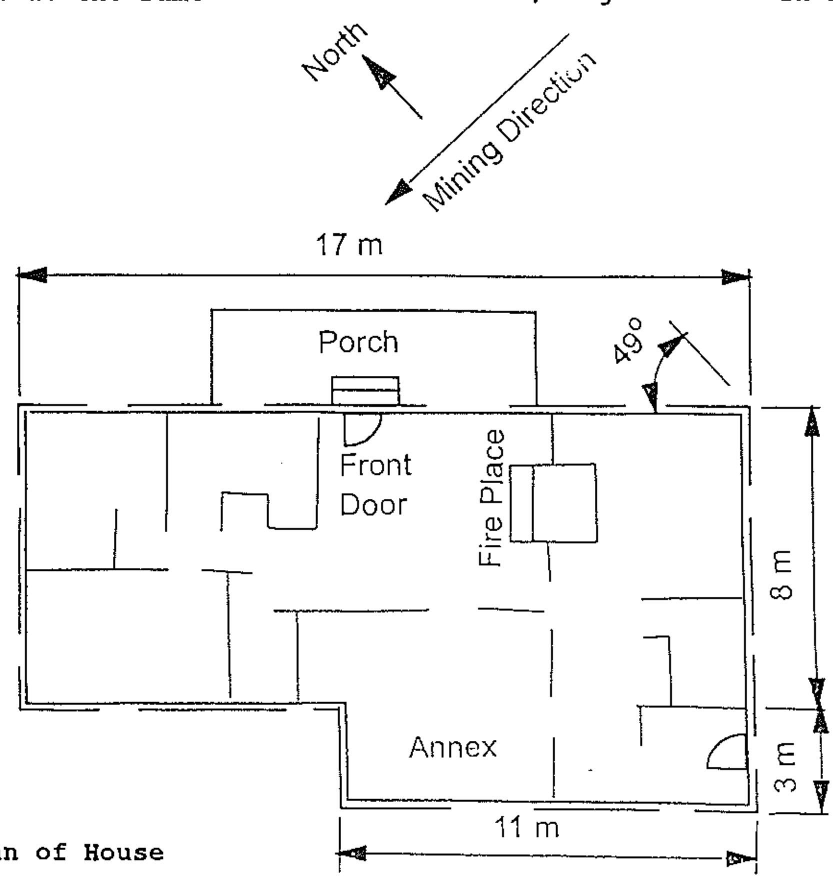


**Figure 1** Floor Plan of House

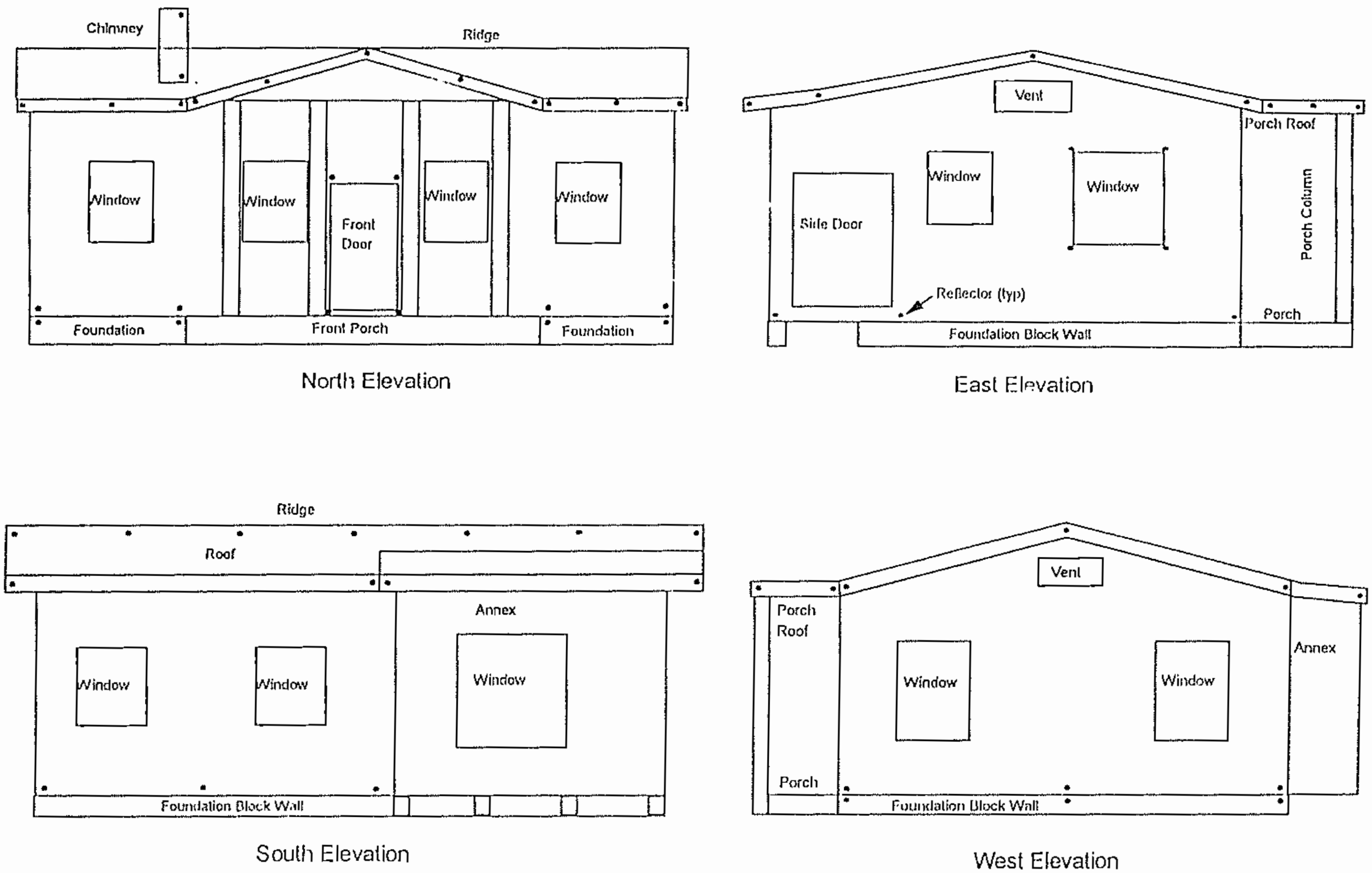


**Figure 2** Elevation Views of House

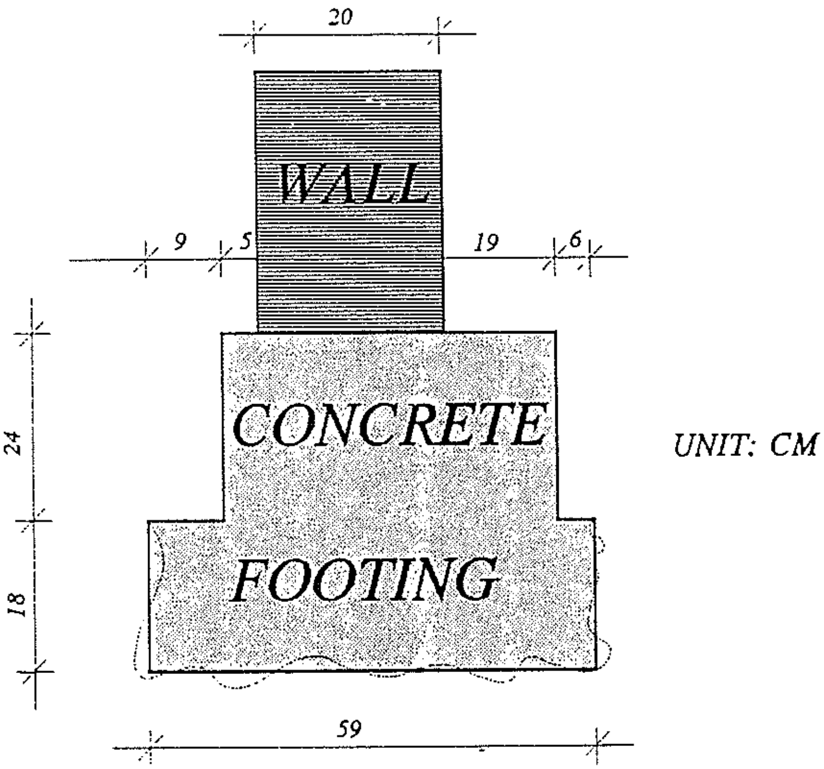


**Figure 3** Typical Section through the Foundation

of 35 degrees, a cohesion value of 4.1 kPa and an elastic modulus of 44 MPa (Lawrence, 1992).

The longwall coal mine panel was 280 m wide, with the house being near the center of the panel. The house was oriented at 40.8 degrees with respect to the mining direction (east-west). Therefore, one diagonal of the house was roughly aligned with the mining direction. The panel was supercritical, meaning the subsidence transverse to the mining direction near the house was relatively uniform. The depth of mining was 160 m, with the coal seam being 2.3 m thick. Mining speed averaged 10.7 m/day and mining progressed from east to west. The mining resulted in a moving ground subsidence wave along the surface approximately 100 m wide perpendicular to the centerline of the mining. It was anticipated that the subsidence effects perpendicular to the mining direction would be minimal.

## Measured Ground and Structure Movements

### Ground Movements

Survey monuments along the access road to the house were monitored during the subsidence event. Figure 4 shows the subsidence profile along the road over a horizontal distance of about 700 m. The relative location of the house is also shown. Figure 4 indicates that a maximum subsidence of about 1.4 meters was measured in the location of the house.

Forty survey monuments were installed on the ground surface around the house. Vertical ground movements were measured with an optical level, and horizontal ground movements measured with an electronic total station survey instrument. The measured vertical ground movements (subsidence) adjacent to the

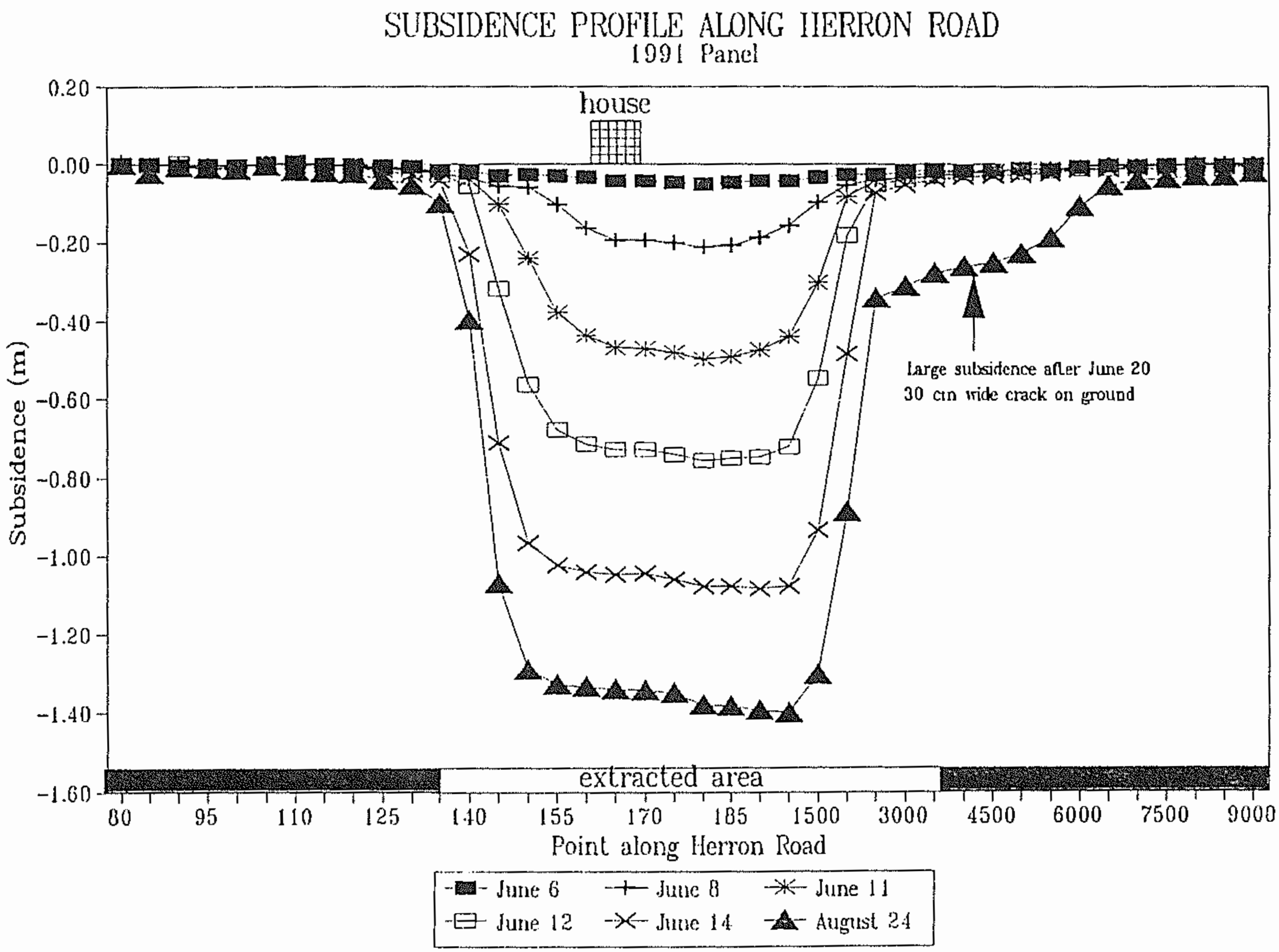


**Figure 4** Subsidence Profile Perpendicular to Mining Direction along a 700 m Survey Line

house are presented in Figure 5. The horizontal ground movements adjacent to the house are shown in Figure 6.

Figure 5 depicts ground subsidence along the mining direction and ground deformation at different phases of the subsidence event. The large span in the east half of the curves corresponds to the rigid front porch. The curves indicate that subsidence started at the east end and moved from east to west. The subsidence profiles on June 15 and 16 indicate that the ground subsided considerably more at the east end than at west end, and suggest the east half of the ground was in tension. On June 17, the tension wave on the ground surface reached the western end of the structure, and the eastern half experienced near constant slope. The entire ground around the house was in compression as the subsidence profiles were slightly concave-upward. The ground returned to almost level by June 24, as the mining face moved well beyond the house. The maximum subsidence around the house was approximately 1.2 m, while the the maximum subsidence in the mining panel was approximately 1.4 m. As anticipated, the subsidence around house was caused primarily by the dynamic subsidence moving in the east- west direction; the subsidence perpendicular to the mining direction was negligible.

The horizontal ground movements in Figure 6 were magnified twenty times for clarity. The ground first moved eastward, then moved westward back to the initial position, with the movements in the north-south direction being negligible. Between June 8 and June 16, the ground at the east end moved the maximum amount (0.164 m) while the ground at the west end only moved about one-third of the maximum (0.046 m). This differential movement perpendicular to the mining direction was negligible.

The horizontal ground movements in Figure 6 were magnified twenty times for clarity. The ground first moved eastward, then moved westward back to the initial position, with the movements in the north-south direction being negligible. Between June 8 and June 16, the ground at the east end moved the maximum amount (0.164 m) while the ground at the west end only moved about one-third of the maximum (0.046 m). This differential movement of 0.118 m subjected the house to tension. On June 17, the east end remained almost in the same position while the west end moved to almost the maximum amount (0.139 mm). On June 18 and 19, the east half of the ground started to move back westward while the west part continued to move slightly eastward, subjecting the house to compression.

House Movements

The horizontal and vertical movements of the house were measured with a total station survey instrument by monitoring the position of seventy reflector monuments mounted on the structure (Lin 1993). In addition, a series of structural tilt measurements were obtained with tiltplates, and soil strain and lateral soil pressures were measured. The locations of the tilt plates, soil strain gages, and soil pressure gages are shown on a plan view of the house in Figure 7.

In general, the house experienced the same movement trends as the ground, being subjected to tension (convex-upward bending), compression (concave-upward bending), and returning to a final state with a small amount of residual tension. However, the magnitudes of deformation were different. The magnitude of the vertical movements of the house were very close to the ground subsidence at the adjacent location, but the horizontal movements of the house were typically smaller than the adjacent ground surface. This difference is a result of the interaction between ground, foundation and superstructure.

Due to the orientation of the house relative to the direction of mining, one diagonal of the house was roughly in the mining direction. The subsidence wave traveled from the northeast corner to the southwest corner. The average horizontal strain of the ground, foundation, wall and roof were calculated along the diagonal to demonstrate the transmission of horizontal strain from the ground to the structure. The results in Figure 8 show discrete tension and compression phases. The maximum tensile strain and compression strain are tabulated in Table 1. Table 1 indicates that the maximum tensile strain of the ground was about 1.6 times the maximum compressive strain of the ground. More tensile strain was

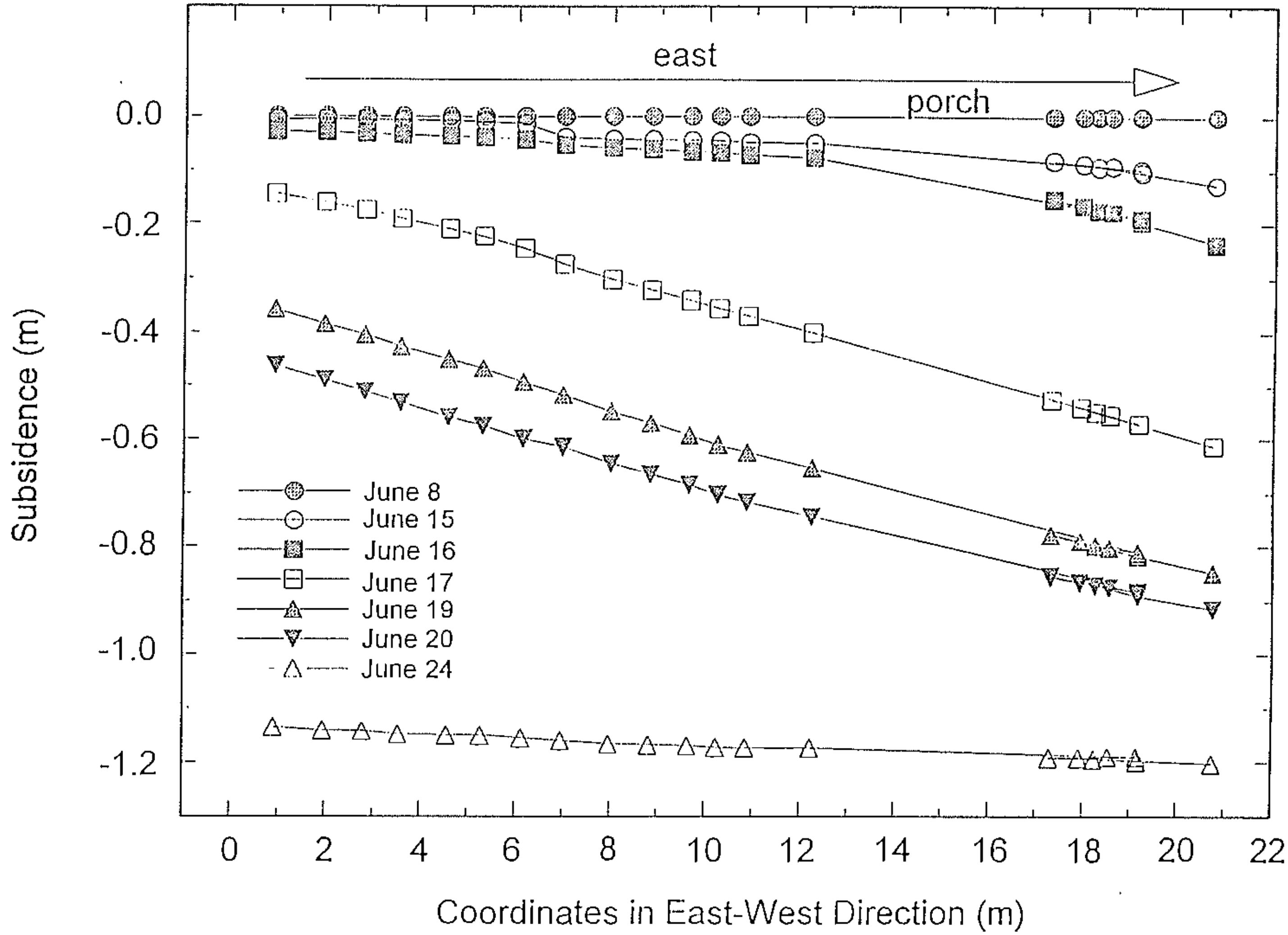


**Figure 5** Subsidence of the Ground near the House

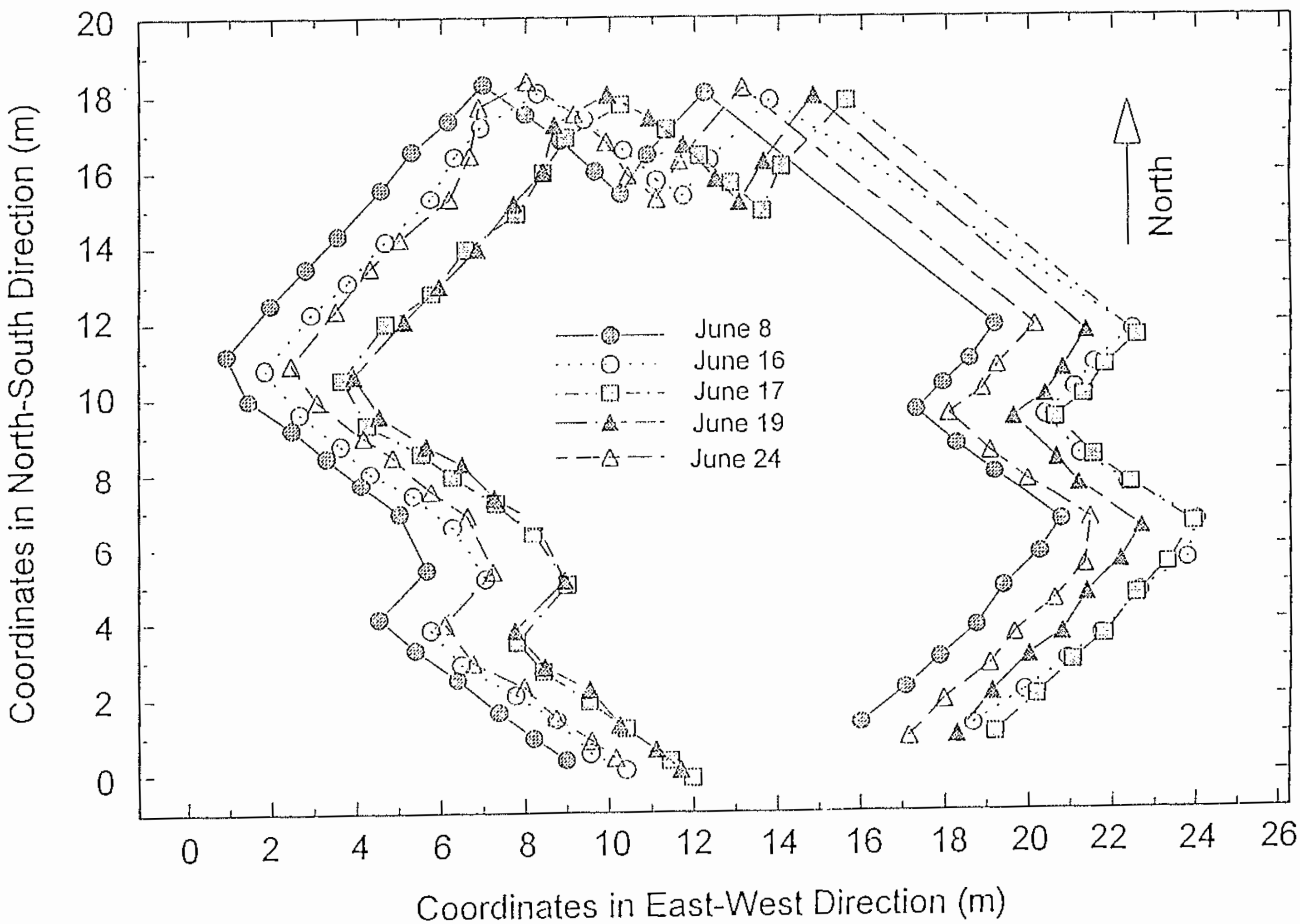


Figure 6 Horizontal movement of the Ground around the House

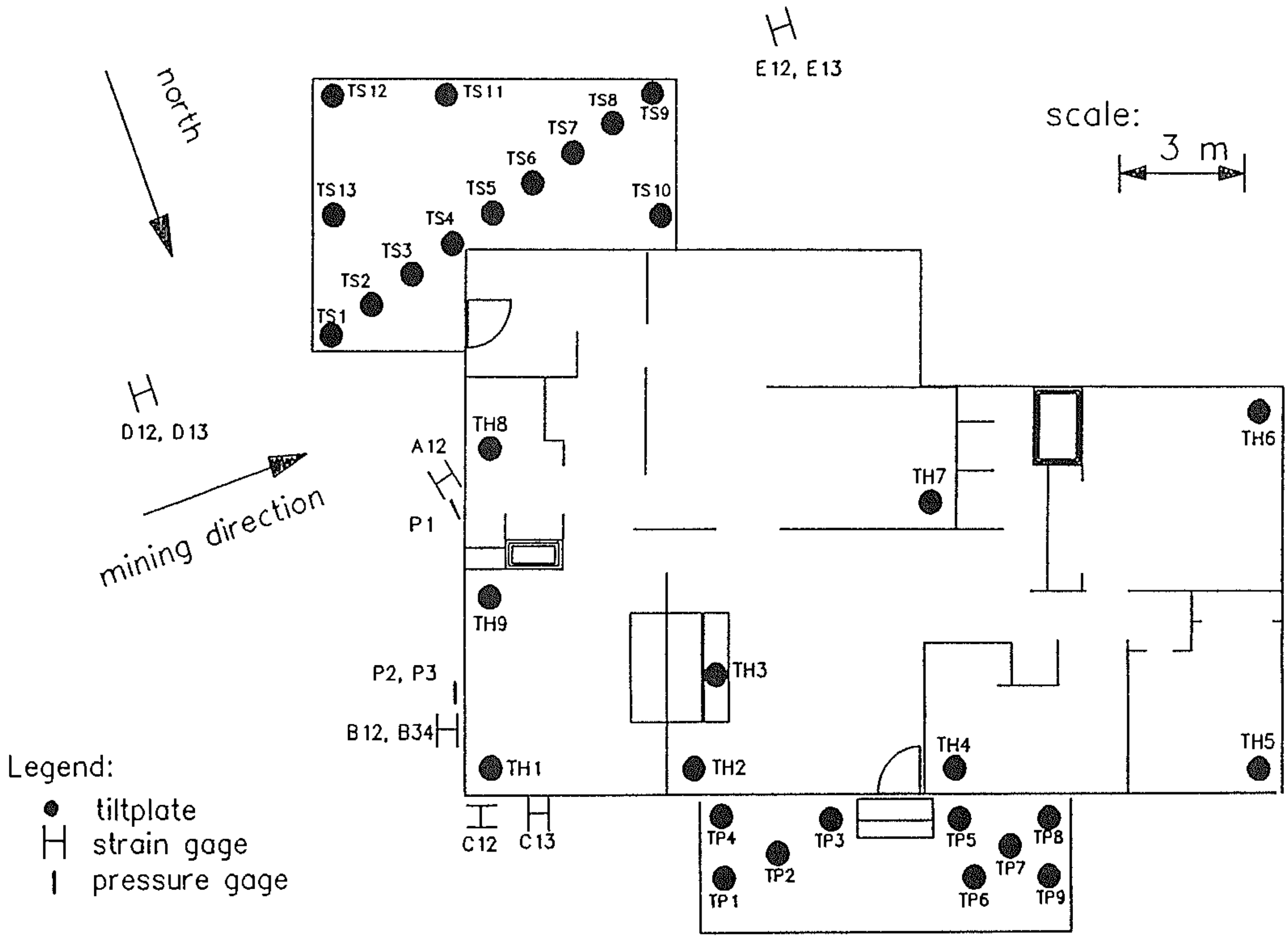


**Figure 7** Instrument Locations on the House

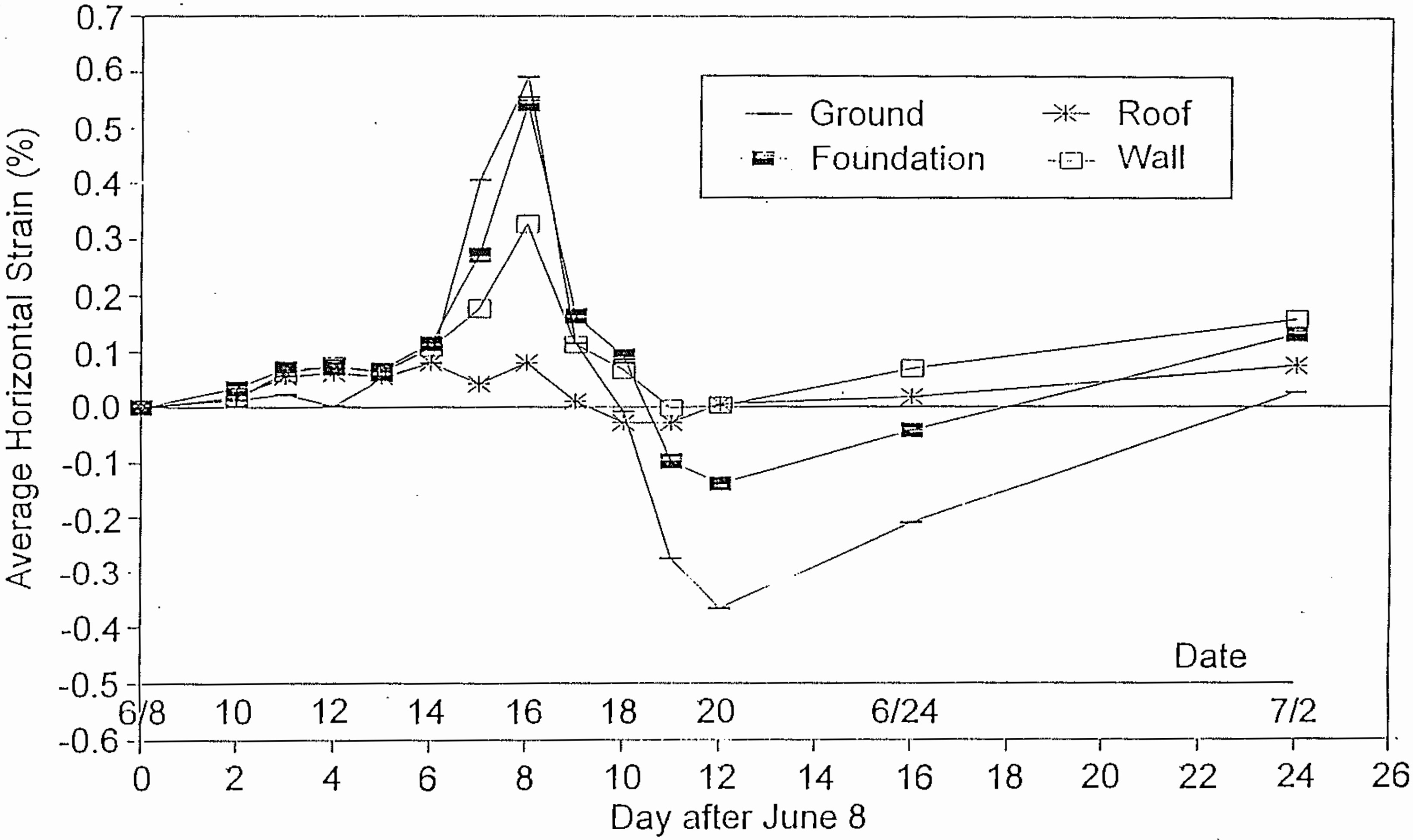


**Figure 8** Average Horizontal Strain of the Ground, Foundation, Wall and Roof

transmitted to the superstructure components than compressive strain. The maximum tensile strain of the foundation was very close to the tensile strain of the ground, while the maximum compressive strain of the foundation was only about one-third of the maximum compressive strain of the ground. Both tensile and compressive strains decreased substantially from the foundation to the roof. Both the wall and the roof sustained virtually no compressive strain along the mining direction, which suggests there were relative movements between the foundation and the superstructure.

Since the longitudinal direction of the house was not aligned with the mining direction, the house was distorted during the passing of the subsidence wave. This distortion consisted of both in-plane and out-of-plane deformation of the structural members. The distortion of the house was measured by the angle formed by the north and west foundation walls as listed in Table 2. The wall angle was observed to increase and then decrease, and be left with an overall decrease in wall angle after subsidence.

Structural Tilt

Tiltplates were installed at numerous locations around the floor ofthe house. The tiltplates (SINCO 1985) permit the measurement of structural tilt in two orthogonal directions. Figure 9 illustrates the East-West tilt measured at two locations (tiltplates TH1 and TH6) over a period of 40 days. It is noted that the maximum tilt occurred about June 18 at the eastern most plate, TH1, while the maximum tilt occurred about 2 days later on the western tiltplate, TH6. There was very little tilt measured at either location in the North-South direction perpendicular to mining.

The gradient of the tilt with respect to horizontal distance is the curvature, which is useful for the comparison of structural damage. A linear regression of the tiltplate data was performed to determine the curvature along the diagonal of the structure. Figure 10 shows the curvature of the house floor over time. During the tension phase (about June 17) a convex-upward or negative curvature of 0.0003 $m^{-1}$ was recorded. On June 21, a concave-upward or positive curvature of 0.00015 $m^{-1}$ was recorded. A second negative curvature of about the same magnitude as the first was recorded on July 2.

**Table 1** Measured Ground and Structural Strain

| | Maximum Tensile Strain | Maximum Compressive Strain |
|---|---|---|
| Ground | 0.59% | 0.37% |
| Foundation | 0.54% | 0.14% |
| Wall | 0.31% | <0.1% |
| Roof | <0.1% | <0.1% |

**Table 2.** Measured Distortion of the House

| Distortion of House as Measured by Angle of the north and west foundation wall | | | | | |
|---|---|---|---|---|---|
| Date | June 8 | June 16 | June 17 | June 18 | June 20 |
| Angle (°) | 90.01 | 90.22 | 90.02 | 89.93 | 89.28 |

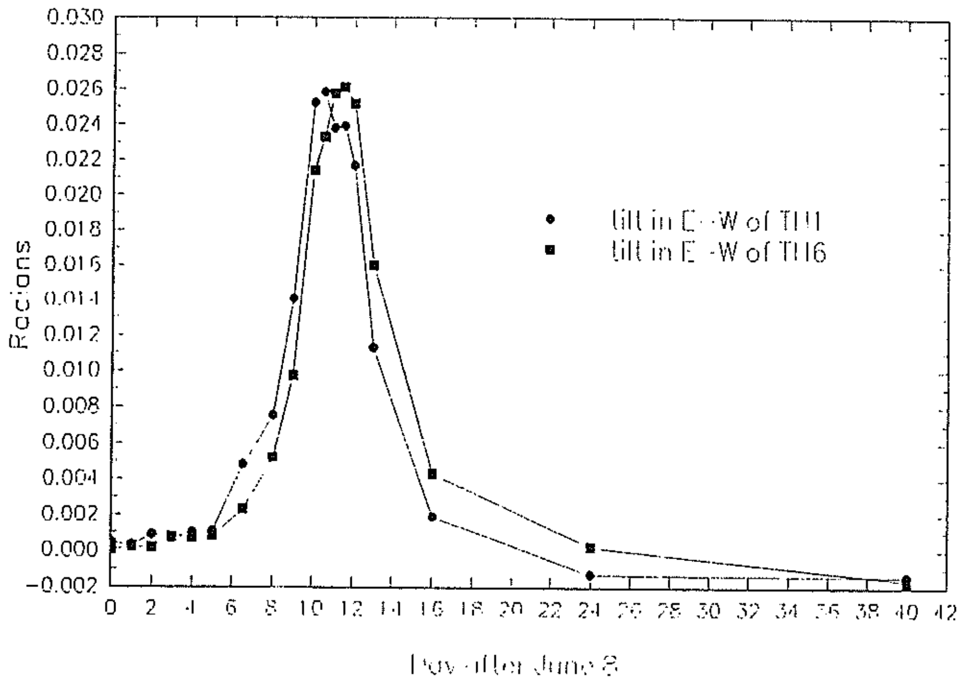


**Figure 9** Measured Tilt of the East and West Corners of the House

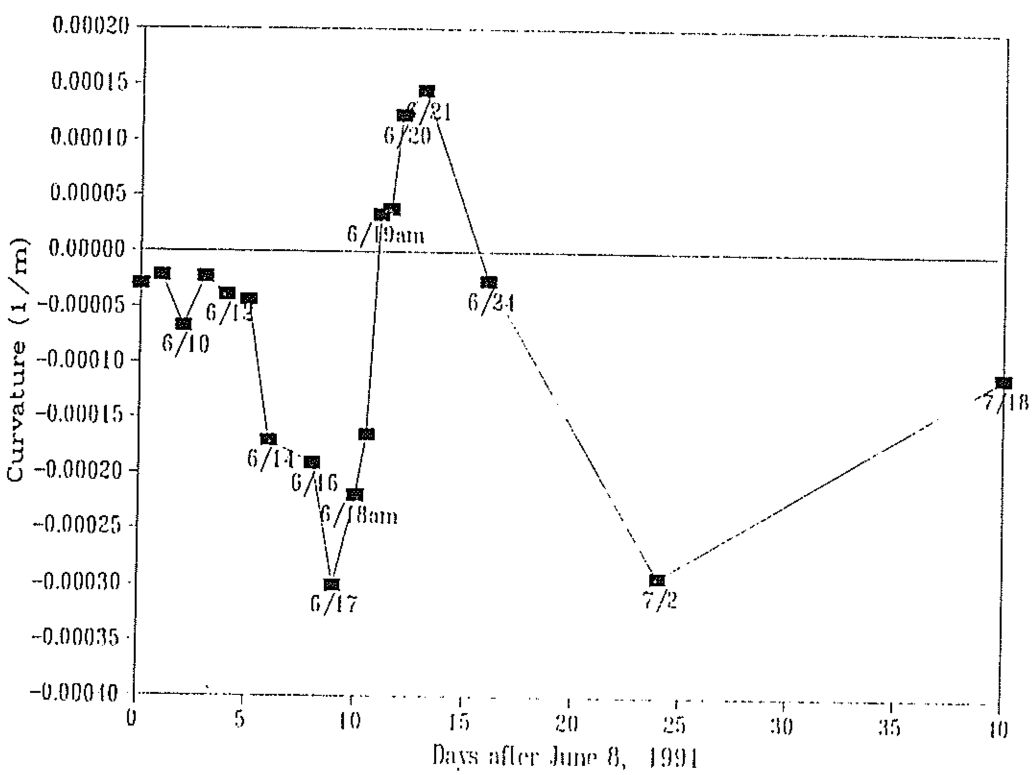


**Figure 10** Calculated Curvatures along the House Diagonal

### Soil Strain

Bison soil strain gages (Selig 1975; Bison Instruments 1989) were installed at several locations to record the soil strain. The soil strain in the horizontal direction is shown in Figure 11 for four locations. Gages A12, located next to the structure, and gage D12 located away from the structure, were oriented in the direction of mining. Gages B34 and C12 were located adjacent to the structure but oriented relative to the structure as shown in Figure 8. Gage A12 was installed at a depth of 0.6 m, while B34, C12, and D12 were installed at a depth of 0.4 m. The overall soil strain response is similar to the average soil strain over the length of the structure shown in Figure 7, with clear periods of tension (positive strain), followed by compression (negative strain). However, the strain magnitudes are different, and the soil strain gages located adjacent to the foundation were left with residual compressive strain after the subsidence wave passed. The residual compressive strain may reflect the plastic deformation that takes place near the footing during the compression phase. This plastic deformation of the soil is thought to cause the residual tension in the footing after the subsidence is complete. The gage length of the soil strain gage measurements was typically about 100 mm, which is much smaller than the gage length of nearly 20 m used to calculate the soil strain in Figure 7. Therefore, differences in the measured strains are not unexpected.

### Soil Pressure

Soil pressure gages were installed to record the lateral earth pressures during the subsidence event. Lateral earth pressures can cause significant damage, especially to structures with basement walls. The soil pressure gages were located between the foundation wall and the surrounding soil. As shown in Figure 8, the pressure gages were oriented with the Bison soil strain gages. The recorded change in soil pressure during the subsidence event is shown in Figure 12. Although the magnitude of the compressive pressure differs from gage to gage, the trend of the pressure variation is similar. A slight negative change or reduction in lateral soil pressure was recorded early in the subsidence event, as the tension wave approached the gage (structure). About June 18, a compressive peak in pressure was recorded corresponding the arrival of the compression wave. This peak was followed by a slight tension period before the pressure returned to nearly that which existed prior to subsidence. The magnitude of the peak compressive stress recorded in the three gages ranged from about 10 kPa to nearly 25 kPa. This is likely a result of differences in the manner in which the gages were installed or seated. In all cases however, the measured stresses were well below the theoretical passive earth pressure which is the maximum pressure that the soil could resist assuming that the wall did not fail. For example, the 25 kPa pressure recorded at gage P2 which was located at a depth of 0.55 m, can be compared to a Rankine passive earth pressure of 35 kPa. This suggests that even though the 25 kPa soil pressure is significant, it is well below the theoretical upper limit.

Since soil pressure gage P1 and soil strain gage A12 were installed at nearly the same location, the results can be combined to produce a lateral stress-strain response curve for the soil as shown in Figure 13. In this curve, the initial tensile strain and pressure are shown as positive, with the subsequent compression loading shown as negative. These instruments recorded much larger strain and stress during the compression phase than during the tension phase.

## Structural Damage

As a result of the ground movements and deformation, the house suffered two types of structural damage: cracking of the concrete footings and block walls, and distortion of the superstructure. The development of cracks in the block wall was recorded during the subsidence. The cracks on the concrete footings were mapped after the subsidence event. The superstructure damage is quantitatively described in terms of strain, tilt and angular distortion.

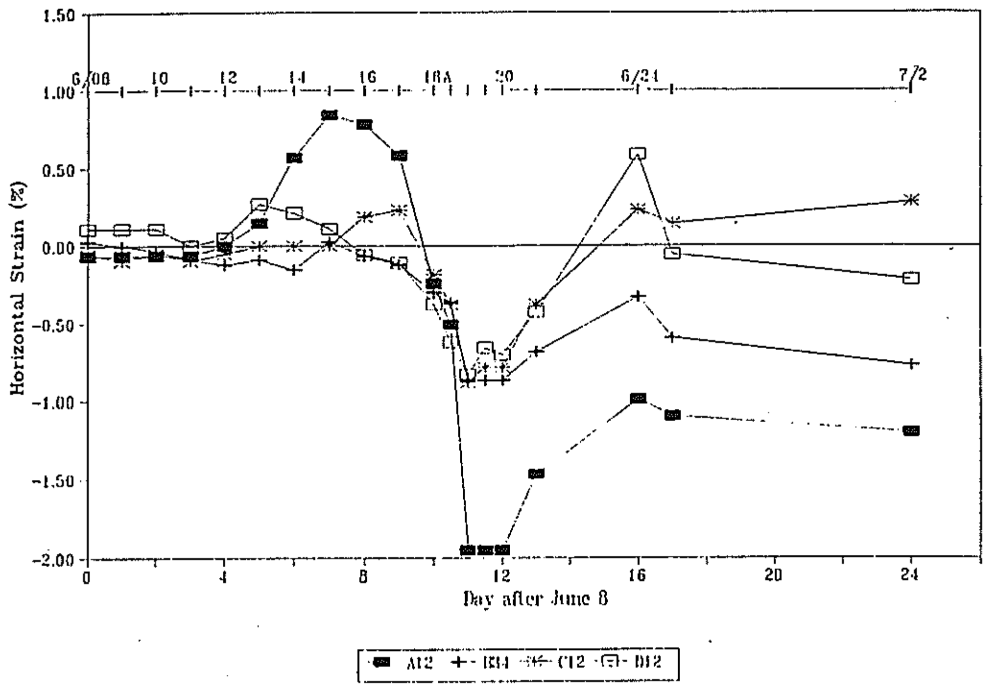


**Figure 11** Measured Soil Strain over Time

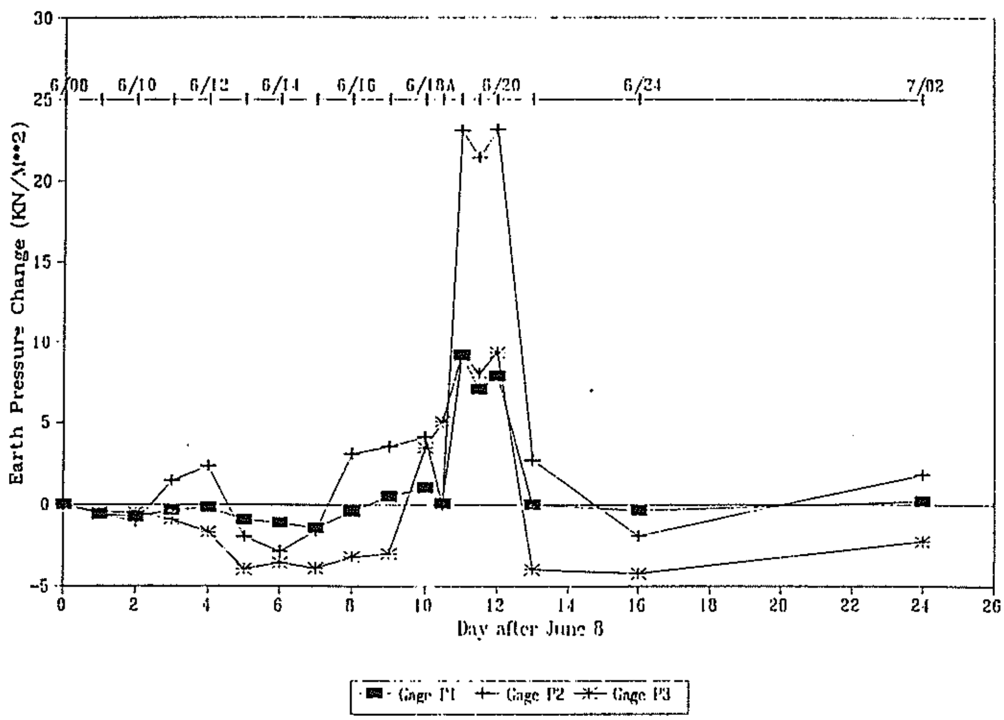


**Figure 12.** Change in Lateral Soil Pressure over Time

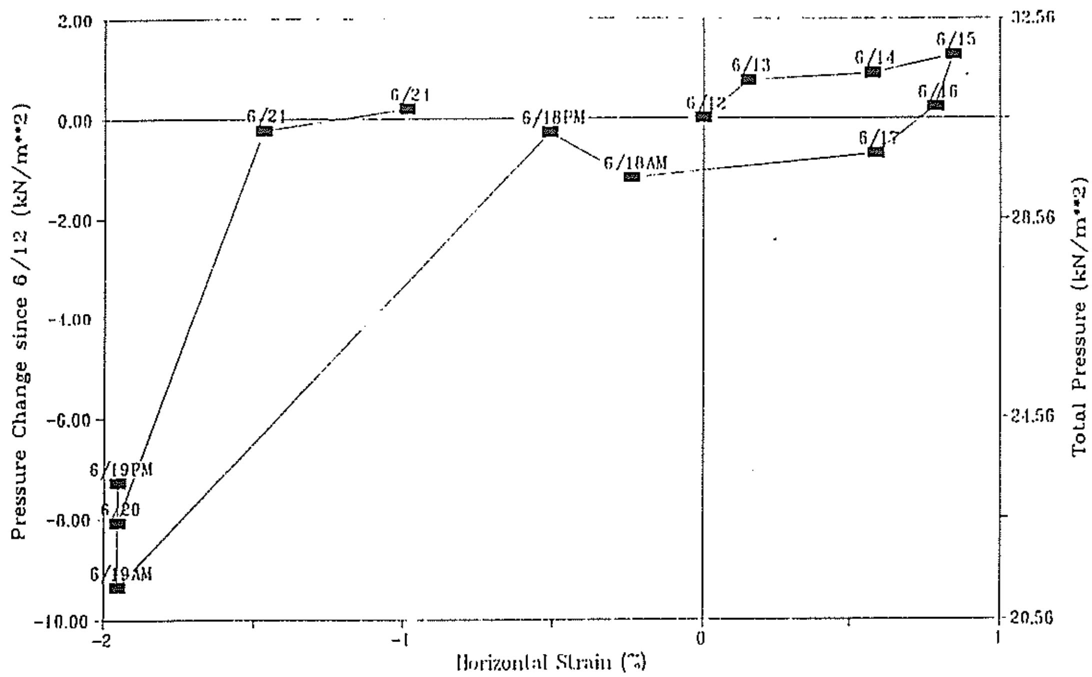


**Figure 13** Soil Stress-Strain response during Subsidence

Figures 14 and 15 show the location and residual crack width in the concrete footings and block walls. The residual crack width was considerably smaller than the maximum crack openings developed during the tension phase of the subsidence event, and ranged from 3 mm to 10 mm. The cracks typically extended up through the masonry wall, generally in a stair step fashion and slightly increasing in width. No cracks were observed in the east side footing, but a large portion of the footing was covered by a utility box. Cracks were first found on the east side of the masonry wall on June 15, and by late afternoon six cracks were found in the masonry wall.

The development of the crack on the east section of the front wall, Figure 14, can be used to illustrate the effects of subsidence on the house. This crack started on June 15 and by the morning of June 16, the blocks on the sides of the crack moved apart about 25 mm both in the direction of the wall plane and perpendicular to the wall plane. On the morning of June 17, the cracks closed to about 10 mm in both the in-plane and out-of-plane directions. The crack decreased to about 2 mm in both directions on June 18. Subsequently, the crack reopened in the wall plane and had a residual width of about 10 mm. This process of tension, compression and a second tension has been described previously (Geddes 1977) and was also observed in a nearby series of test foundations (Lin et al. 1994). Due to the high compressive stiffness of the structure and yielding of the soil, the full compressive deformations from the soil are not induced into the structure. As the ground returned to a state of zero tension, it induced a second tension in the structure.

Additional damage to the masonry wall was observed where the center beam rested on the wall. During the compressive phase of the subsidence, the beam pushed two blocks out about 10 mm on both the east and west sides, causing some local crushing of the block. This is indicative of the relative movements between the foundation and superstructure.

Cracks were also observed on gypsum wallboard inside the house. These cracks typically developed at an about 45° angle from the corner of openings such as windows and doors. These cracks were

Final Cracks in Foundation (Looking East)

Unit of Crack Width: mm

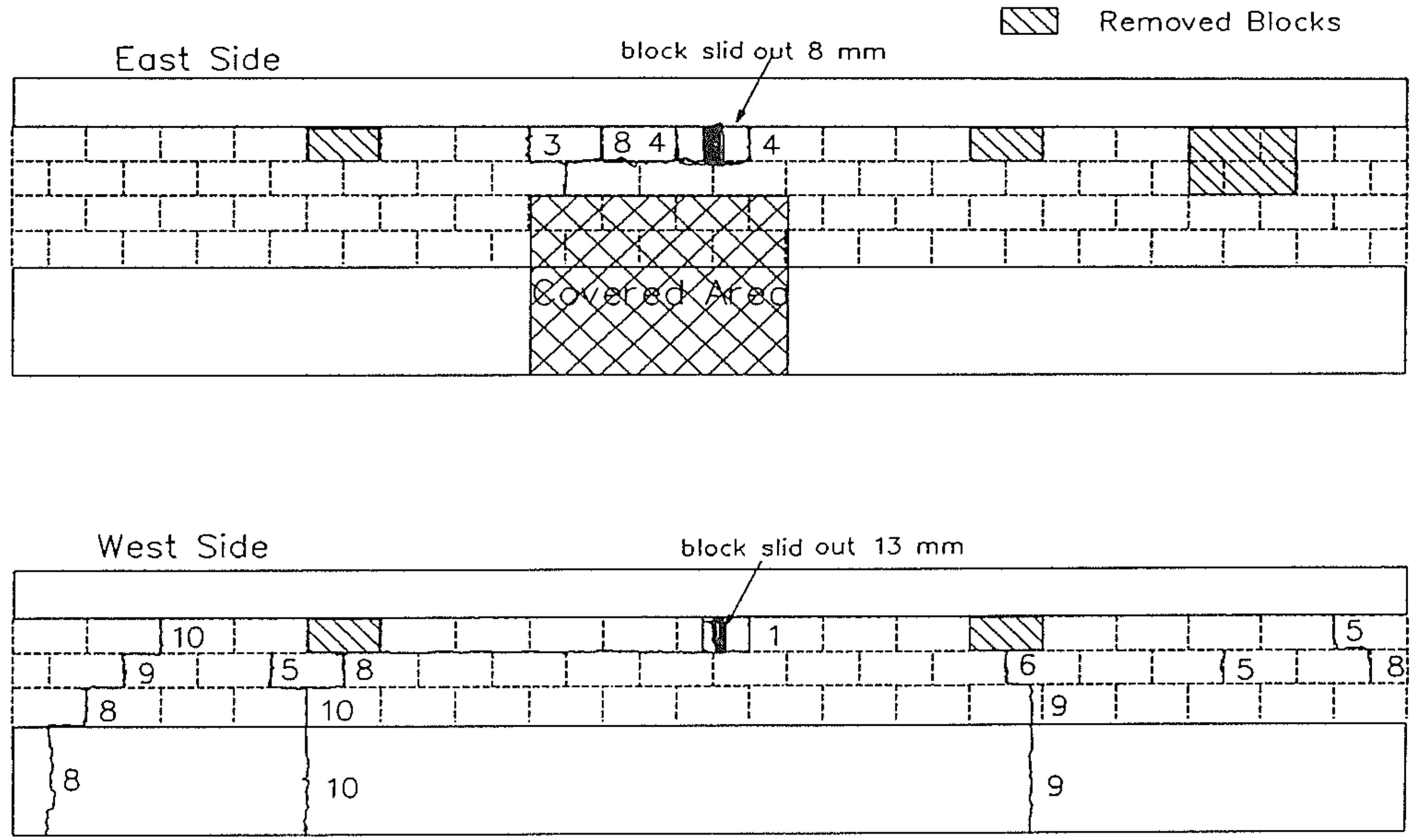


**Figure 14** Location and Widths of Final Cracks (Front and Rear of House)

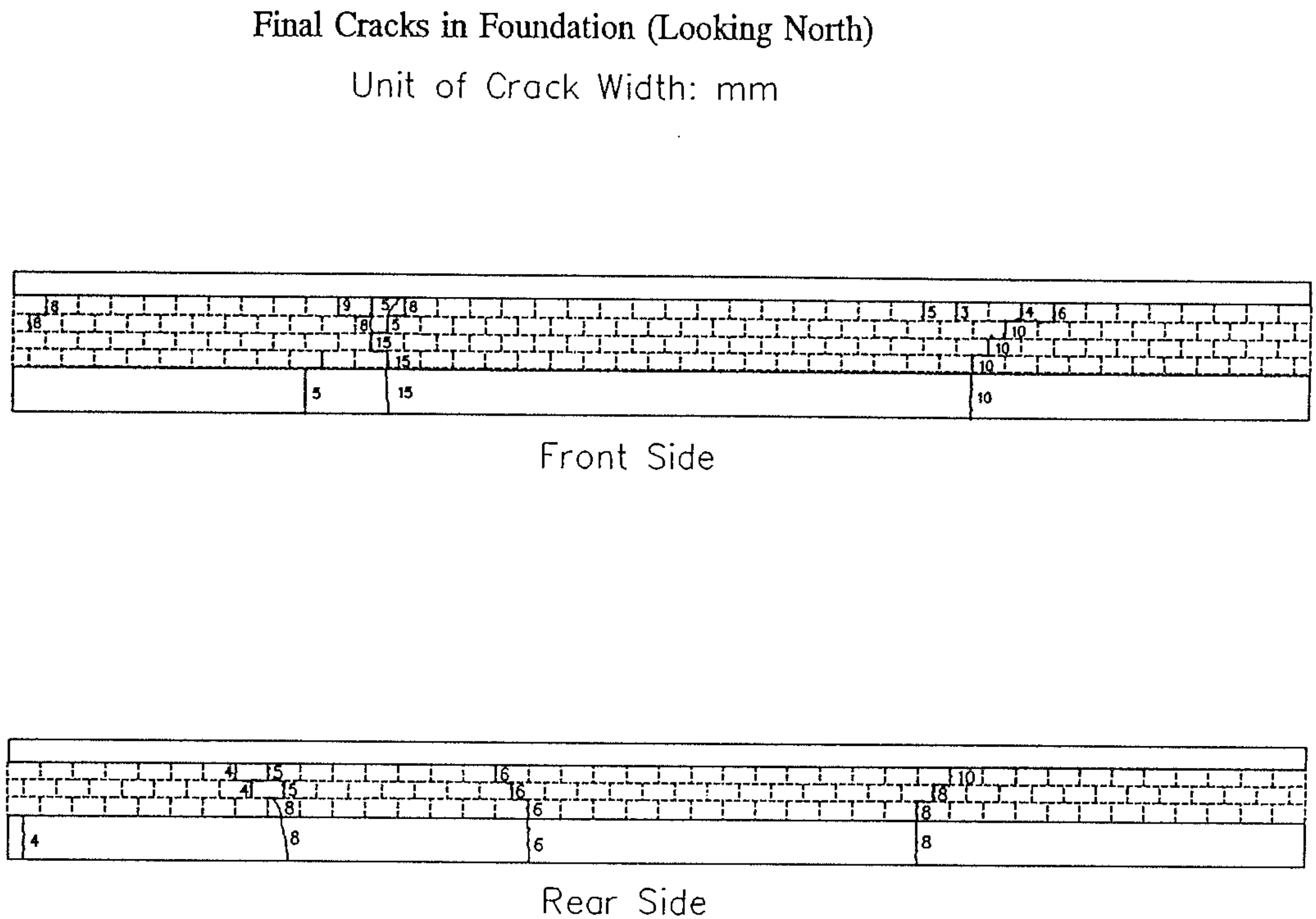


**Figure 15** Location and Widths of Final Cracks (East and West Sides of House)

typically very small in width and extended less than 300 mm.

It appears that the superstructure damage was primarily due to differential vertical movements, and secondarily due to horizontal movements. The structural deformation and damage were quantitatively described in terms of angular distortion. Angular distortion is the change of slope between two points divided by the horizontal distance between the two points. Figure 16 shows the angular distortion of the ground, foundation wall, and house wall immediately above the foundation wall. The angular distortion decreases moving from the ground up to the foundation, and continues decreasing with elevation into the structure. The change in angular distortion is indicative of interaction between ground, foundation and the superstructure.

The calculated angular distortions are relatively consistent with the limits of angular distortion suggested by others corresponding to certain levels of structural damage. Bjerrum (1963) suggested an angular distortion of 1/500 as a safe limit for no cracking. Cracking was observed in the house foundation when this limit was exceeded. Marino (1985) suggested that a house with a crawl space that had an angular distortion exceeding 1/208 would require foundation repair. Once the house foundation cracked, it essentially followed the ground movements, resulting in high angular distortion of much greater than 1/208 and complete failure. Wahls (1994) indicates that cracking for plywood or fiberboard on wood frames occurs at an angular distortion between 1/60 and 1/170. Angular distortions greater than 1/170 were observed during the investigation, but only minimal cracking was noticed. However, serviceability problems such as inoperable doors were experienced.

## Conclusions and Recommendations

The foundation of the monitored house cracked in numerous places during the mining subsidence. Therefore, extensive repair and replacement work would be required before the house could be returned to normal use. Despite the extensive damage to the foundation, the superstructure of the house suffered minimal damage. The superstructure damage was primarily serviceability issues such as sticking doors and

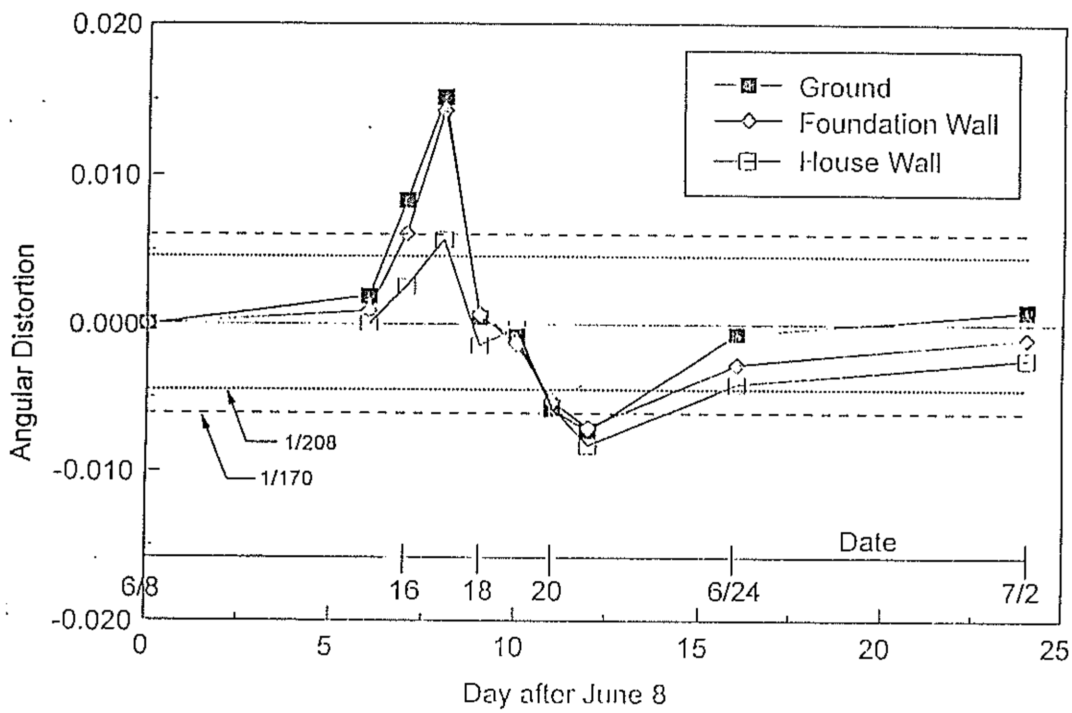


**Figure 16** Angular Distortion of Ground, Foundation Wall, and House Wall

aesthetic problems such as cracking of the interior gypsum-board wall. The wall deformations were mainly in-plane shear and out-of-plane movements resulting from twisting of the house.

The house approximately followed the nearby ground subsidence in the vertical direction. Measurements of strain over the length of the house suggest that the foundation experienced tensile strains close to those in the ground during tensile period, resulting in cracking of the foundation and wall. However, during the compression period, the foundation cracks closed and the house frame distorted, resulting in foundation strain that was only about one-third of the strain in the ground. The foundations and walls experienced both in-plane and out-of-plane deformation but the walls appeared more vulnerable to the out-of-plane deformation. The deformation in the foundation was transferred to the superstructure primarily through the mechanism of shearing, and its magnitude decreased from foundation to roof.

The minimal damage to the house superstructure can be attributed to the lack of any significant connection between the superstructure and the foundation. Although this lack of connectivity between the structure and foundation tended to reduce the damage, this cannot be recommended as an damage mitigation technique. Good construction practice dictates anchoring the structure to the foundation to resist lateral loads due to wind and earthquakes, even if the anticipated lateral loads are small.

The purpose of a foundation is to transfer structural load to the ground and to minimize settlements. In an area subject to mining-induced settlements, there are several other considerations during foundation design, most at very little additional construction cost. Damage mitigation schemes for mining subsidence or other similar types of ground movements should be directed towards strengthening the foundation and improving the connection between the foundation and the superstructure. Reinforcing steel and post-tensioning were proven to be effective in minimizing foundation cracking or controlling crack widths in a series of test foundations constructed over a similar mining panel (Lin et al. 1995). By reinforcing and tieing the basement/crawl space walls and possibly the superstructure walls to the foundation so that they act compositely, a stiff and strong beam is formed to resist the ground movements. Additional research is being conducted to further develop this concept.

Mine subsidence results in a dynamic subsidence wave that moves along the ground surface. This wave produces three phases deformation for a structure on the surface: a) convex-upward bending or tension phase, b) concave-upward bending or compression phase, and finally c) a second tension or return to near horizontal configuration. In general, the ground returns to a near zero state of stress in the third phase, but the structure may be left with some residual tension.

When analyzing structures for subsidence deformation, it is important to keep in mind that due to soil-structure interaction effects, the ground deformations in the vicinity of the structure are smaller than those away from the structure. Therefore, a structure need not resist the full magnitude of ground deformation measured during subsidence event. The degree of soil-structure interaction depends upon the relative stiffness of the soil and foundation. The vertical deformations are believed to cause the structural damage, with horizontal deformations serving to open up any cracks that form due the vertical deformation.

Acknowledgments

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