CONTINUOUS LIFT PIERS: DAMAGE REPAIR AND RESPONSE DURING SUBSIDENCE[1]

Eric C. Drumm[2], Richard M. Bennett[2], Guoming Lin[3],
David B. Raaf[4] and Dean Daugherty[5]

Abstract: A series of test foundations damaged during a longwall mining operation were left with permanent tilt, curvature, and substantial cracking. Two of the foundations were releveled using continuous lift piers. The continuous lift piers removed the tilt and curvature and significantly reduced the width of the foundation cracks. Following the releveling of the foundations, an adjacent longwall panel was mined, resulting in additional subsidence, although of smaller magnitude. The response of the releveled foundations was monitored and compared with the response of a footing that was not releveled. Although the continuous pier system does not strengthen the structure and distortion was observed during the second event, the system permitted the deformations to be removed in a few hours.

Introduction

Ground subsidence due to underground mining activities is a significant problem affecting mine operators, the insurance industry, government agencies, and property owners. In the United States, damage to residential structures from underground mining is estimated between $25 and $35 million each year (Gray 1988). With approximately 5.2 million acres of abandoned or inactive coal mines, of which 500,000 acres are in populated urban areas (Dyni and Burnett 1993), damage repair techniques applicable to residential and light commercial structures must be developed. Effective damage remediation methods can only be developed with a good understanding of the mechanisms causing structural distress. Since structures in subsidence prone areas are often subjected to multiple or recurring ground deformation events, the response of repaired structures during subsequent subsidence events must also be evaluated.

Damage to structures from subsidence occurs primarily over inactive or abandoned room-and-pillar mine operations and may occur many years after the coal has been extracted. Since modern longwall techniques result in subsidence that is immediate and can be predicted with some degree of certainty, structural damage can often be reduced or eliminated by premining measures. Although damage due to longwall mining is not as significant an economic issue as damage from abandoned mine operations, the controlled nature of longwall induced subsidence provides a good opportunity to observe the mechanisms governing structural damage.

The response of structures to mining induced subsidence is complex. Structural behavior and damage are dependent upon the relative properties of the foundation and underlying soil, and depend significantly on the magnitude of the ground movements. This coupling of soil and structural response is known as Soil-Structure-Interaction (SSI). Monitoring full-or reduced-scale structures during subsidence has provided useful observations

[1]Paper presented at the International Land Reclamation and Mine Drainage Conference and Third International Conference on the Abatement of Acid Drainage, Pittsburgh, PA, April 24-29, 1994.

[2]Eric C. Drumm and Richard M. Bennett, Associate Professor, Department of Civil and Environmental Engineering, The University of Tennessee, Knoxville

[3]Guoming Lin, Engineer, S&ME, Savannah, GA

[4]David B. Raaf, President, Atlas Systems, Inc., Independence, MO

[5]Dean Daugherty, Atlas Foundation Repair Systems, St. Louis, MO

Proceedings America Society of Mining and Reclamation, 1994 pp 314-321
DOI: 10.21000/JASMR94040314

https://doi.org/10.21000/JASMR94040314

regarding damage and SSI effects (Walker 1987, Powell et al. 1988). In a more recent series of field tests (Bennett et al. 1992), some test foundations damaged by subsidence were releveled using continuous lift piers. To evaluate the application of continuous lift piers for subsidence damage remediation, the response during a subsequent subsidence event was observed.

Test Foundations

Six test foundations were constructed over a longwall panel in West Frankfort, IL (Kane et al. 1990) with the undermining to take place in 1990. The six foundations were built to simulate typical residential or light commercial construction. Constructed of identical size, the six foundations differed in the method of footing construction. Only three of the foundations will be described here: the plain concrete footing, the reinforced concrete footing, and the post-tensioned concrete footing. Details of the other foundations are described by Bennett et al. (1992). A schematic of the test foundations is shown in figure 1, with the residential loading simulated by soil-filled load bins placed on top of the footings. The foundations were built in the anticipated zone of maximum tension, near the edge of the 1990 panel. The location of the foundations relative to the first (1990) and second (1991) longwall panels, is shown in figure 2. The coal seam was about 2.3 m thick, at a depth of about 160 m. A firm layer of shale was located at a depth of approximately 7 m. The longwall panel was 280 m wide and 1950 m long.

Response to Initial Subsidence Event

The maximum subsidence from the first panel measured at the panel centerline was 1.43 m, while the subsidence in the maximum tension zone near the test foundations ranged from 0.1 m toward the edge of the panel to 0.3 m toward the centerline of the panel. Footing deformation was measured with a precision survey level and tiltmeter. The maximum differential settlement of the plain concrete footing was 0.170 m, which resulted in an average tilt of 0.0139 radians. The reinforced concrete and post-tensioned concrete footings sustained similar deformations. Figure 3 compares the cracks observed in each of the three footings. The plain concrete footing suffered the most damage, cracking in three locations with the maximum crack being 18 mm wide. The post-tensioned footing did not crack and the deformed bar reinforced footing developed small cracks. The block walls

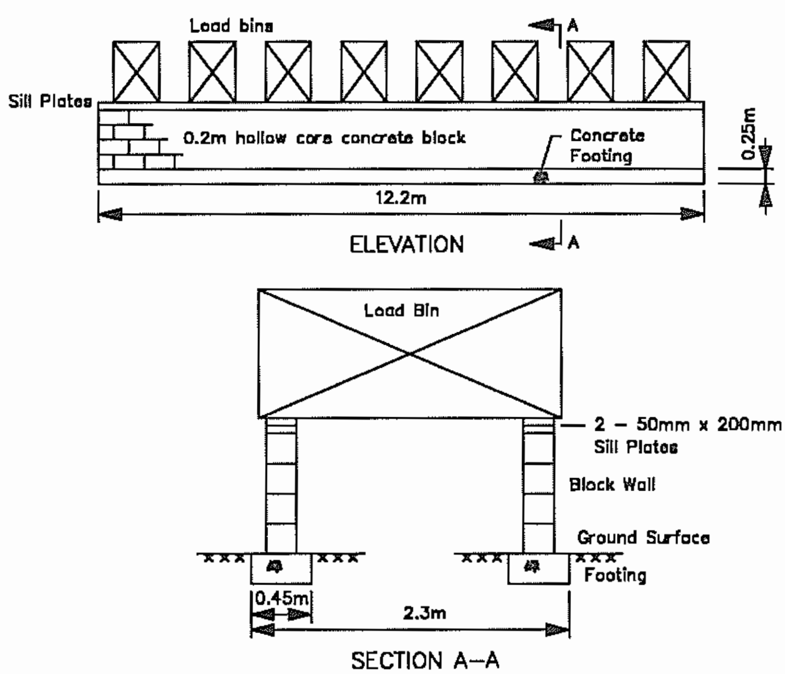

Figure 1. Schematic of test foundations and load bins.

cracked at the locations over the footing cracks, and the wall cracks were slightly wider than the footing cracks. The deflection ratio (DR) is defined as the maximum footing deviation from a straight line divided by the foundation length. Values for deflection ratio and average curvature for the test footings and surrounding soil are summarized in table 1.

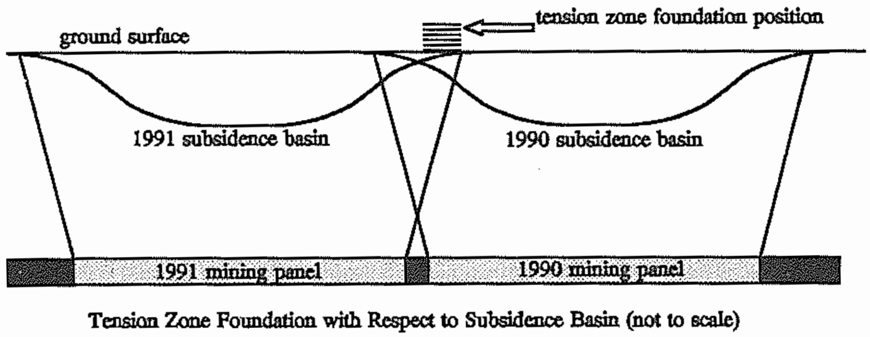

Figure 2. Relative location of tension zone foundations with respect to 1990 and 1991 mining panels.

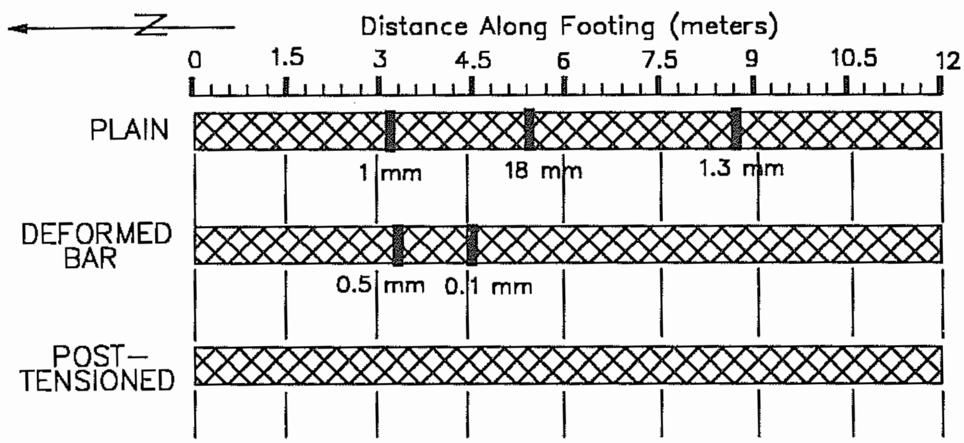

Figure 3. Cracks in foundations due to first subsidence event.

Table 1. Deflection ratio and curvature due to first subsidence event

Footing	Ground	Plain Concrete	Reinforced Concrete	Post-Tensioned Concrete
Deflection Ratio	-0.00386	-0.00248	-0.00233	-0.00212
Curvature (1/m)	-0.00148	-0.00160	-0.00154	-0.00138

Foundation Restoration with Continuous Lift Piers

After subsidence, the plain concrete and reinforced concrete footings were releveled using a system of continuous lift piers (Atlas Systems, Inc. 1990). Once installed, continuous lift piers permit the foundation to be raised or lifted over a wide range, with a high degree of control. The system also permits additional adjustments to the foundation should ground movements occur in the future. The Atlas pier system is a proprietary system (Atlas System 1990), and the installation is described in terms of this method. Other systems with similar capabilities exist, but have not been demonstrated on subsidence-damaged structures.

Releveling the foundation can correct the effects of subsidence such as residual tilt and curvature, which may cause sticking doors and windows, and can return the structure to service. However, the continuous lift pier system does not increase the structural capacity of the foundation and does not stiffen cracked elements. The method should be compatible with structural measures (Marino 1992) to restore the structural capacity. The goal of this investigation was to determine how a subsidence-damaged structure, restored to service with continuous lift piers, would respond to a second subsidence event, and to demonstrate the ability to relevel the foundation after the second event. Foundation restoration with the continuous lift pier system consists of two phases: the installation phase, and the lift phase.

Continuous Lift Piers - Installation Phase

The footing is excavated at the pier locations to provide access to the sides and bottom. If cracks exist in the footings, steel angles or plates are bolted to the footing to maintain continuity across the cracks during the leveling process. A temporary pier bracket is then bolted to the footing, as shown in figure 4. The cylinder drive assembly is then installed to hydraulically push the pier sections down to a firm bearing strata. If the firm layer is deep or nonexistent, friction must be developed along the mini-piles. To provide adequate reaction for the hydraulic driving forces, supplemental weights can be added to the foundation, or reaction can be obtained from helical outriggers as shown in figure 4. For the test foundations, five continuous lift pier systems were installed on each of the two foundations. The pier sections were pushed to the firm strata at a depth of about 7 m from the original ground surface. Reaction for the pier jacking was provided by supplemental weights added to the top of the foundations.

Continuous Lift Piers - Lift Phase

After the pier is in place, the supplemental weights, cylinder drive assembly, outriggers, and helixes are removed, and the temporary pier bracket is replaced by the continuous lift bracket assembly (fig. 5). A hydraulic lifting jack is installed at each pier location, and the jacks connected to the hydraulic pump through a manifold. The manifold system permits the simultaneous adjustment of each of the piers to prohibit additional structural distress and ensure that the foundation is releveled.

Using the manifold system, the footings were systematically raised and the foundations leveled. The maximum differential settlement before leveling was 0.24 m measured on March 21, as shown in figure 6. After leveling, June 10, the foundation was essentially level, with the south end slightly higher than the north end. The maximum difference was 0.0524 m on June 10. The footing could have been completely leveled, however, adjustments were made until the sill plate was level within 3 mm. Crack widths in the footings and block walls decreased after leveling. The adjustment heads were left in place to facilitate leveling after the second subsidence event. However, if additional ground movement is not expected, the lifting heads can be removed to restore the original foundation appearance. A significant advantage of the continuous lift pier system is that if additional deformation occurs, the footing can be releveled or adjusted. The installation and releveling were completed in two days. If the helical outrigger system had been used to provide the reaction, the installation period would have been significantly shorter than that required with the supplemental weights.

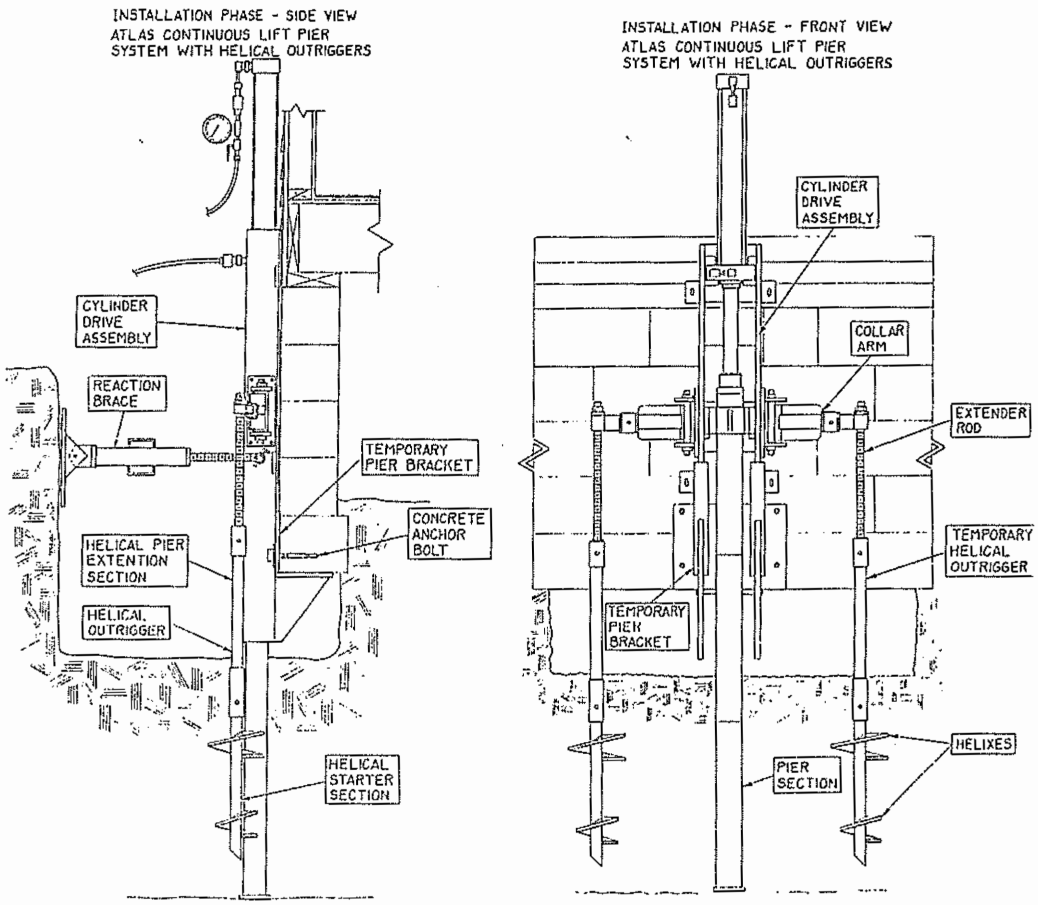

Figure 4. Installation phase-continuous lift pier system with helical outriggers.

Response of Restored Foundations During the Second Subsidence Event

The foundations were monitored during the second (1991) subsidence event with a precision level and tiltmeter. The deformation of the nearby ground was measured with a level and total station. Subsidence from the first (1990) panel was essentially complete by August 1990, and subsidence from the 1991 panel was not significant until late June 1991. The subsidence of the reinforced concrete footing is shown in figure 6. Maximum subsidence was about 0.26 m, with slightly more settlement at the north end than the south. Unlike the first subsidence event, the second event yielded nearly uniform ground deformations, resulting in minimal curvature in the foundations. During the 1991 subsidence, the foundations were located just outside the zone where maximum tension is expected, as shown in figure 2.

The variation in the deflection ratio over time is shown in figure 7 for each of the three footings. All three footings experienced a significant increase in DR during the second subsidence event, but the reinforced concrete and post-tensioned footing deformed less than the plain concrete footing (table 2). This difference was observed during the first (1990) subsidence event also, except the deflection ratios were much greater, about -0.002. It can be concluded that since the continuous lift piers did not increase the structural rigidity of the footings, they did not improve the resistance to deformation during subsidence. However, since the reinforced footing with continuous lift piers and the post-tensioned footing without continuous lift piers responded in a similar manner, the continuous

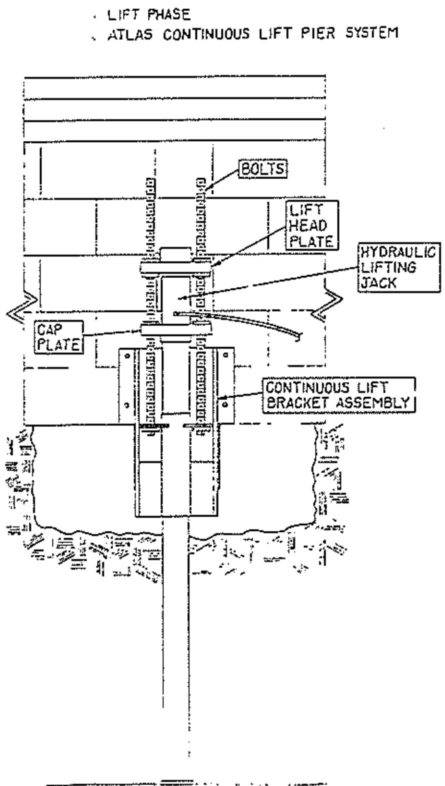

Figure 5. Lift phase-continuous lift piers.

lift piers did not exacerbate the subsidence deformations. Once the continuous piers are in place, the foundation can readily be restored to service.

Tilt of about 0.002 radians was measured at the north end of the reinforced footing, and 0.005 radians at the south end. Except for the plain concrete footing, which had some tiltplates damaged during the pier installation process, similar values were obtained for the other footings. The tilt was calculated with respect to June 10, 1991. The majority of the tilt and deformation occurred between June 19 and July 18. Since the change in tilt was nearly constant, the curvature was assumed to be constant. Curvatures were calculated by obtaining a slope from a linear regression of the tilt values along the footings, and are summarized in table 2. The curvatures experienced by the 1991 event were about one fifth that experienced during the 1990 event, which is consistent with the location of the footings relative to the longwall panel. The footings were constructed within the zone of anticipated maximum tension for the 1990 panel, but were about 50 m away from the zone of maximum tension for the 1991 panel.

According to a damage criterion proposed by Bhattacharya et al. (1984), a brick or masonry structure is liable to suffer functional damage at a deflection ratio of 0.0005 or a curvature of 0.00005 (1/m). The actual relationship between curvature and deflection ratio of a structural element depends on the length of the structural element. For the test footings, it was determined (Lin 1993) that the curvature is about two-thirds of the deflection ratio. The measured deflection ratios and curvatures during the 1990 and 1991 subsidence events also verified the relationship. The deflection ratios caused by the 1991 subsidence were around 0.0003, and no significant additional damage was observed. Therefore, the above proposed criterion in terms of deflection ratio was more appropriate, while the curvature value was overly conservative for the footings.

Table 2. Final curvatures and deflection ratios After second subsidence event.

Footing	Plain Concrete with Atlas Pier	Reinforced Concrete with Atlas Pier	Post-Tensioned Concrete Not-Repaired
Deflection Ratio	0.00046	0.00029	0.00028
Curvature (1/m)	NA	0.00026	0.00019

NA = Not available

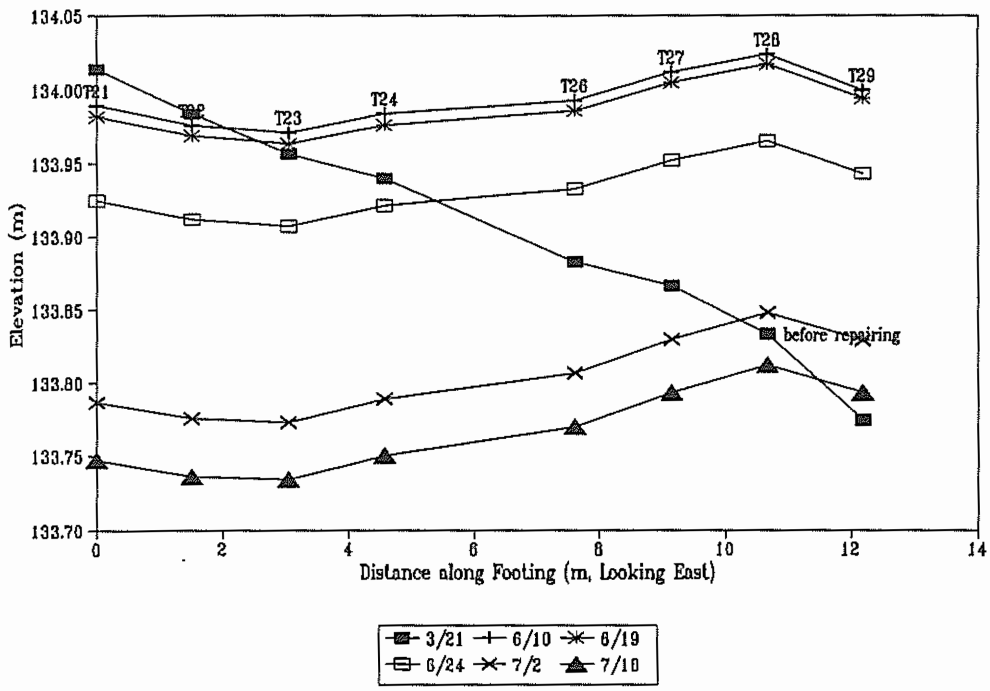

Figure 6. Elevation profile of reinforced concrete footing before and after leveling.

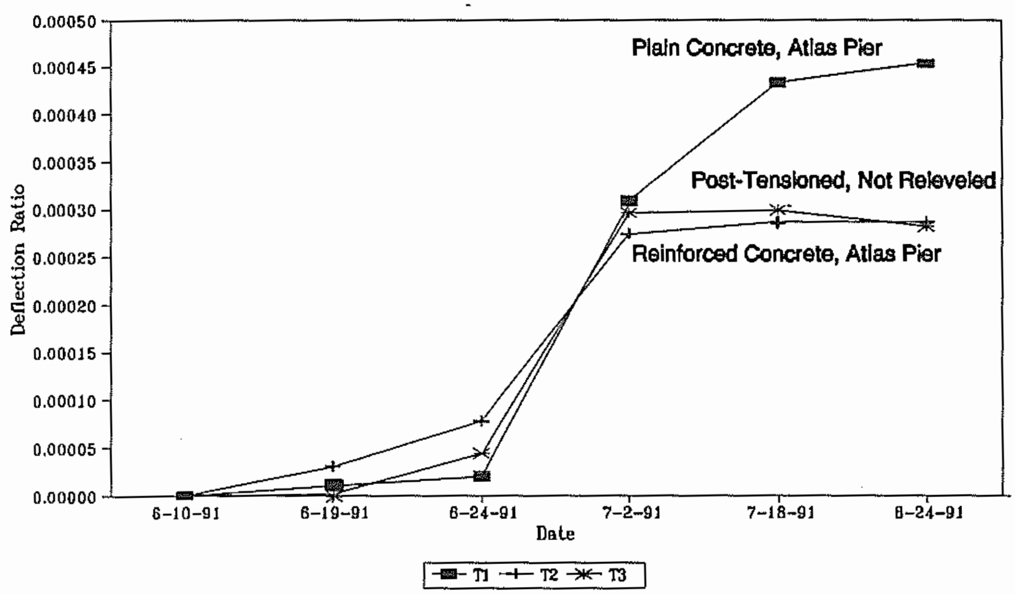

Figure 7. Foundation deflection ratio during second subsidence event.

One of the most significant advantages of the Atlas continuous lift pier system is that after installation, the position of the structure can be adjusted repeatedly. The tilt and deformation left in the foundations after the second subsidence event were removed in 1993, restoring the foundation to level. Since the lifting heads were left in place, the releveling process was completed in about two hours, simply by reinstalling the jack and manifold system. Provided adequate travel is provided in the original installation, there is no limit to the number of times the structure can be releveled.

Conclusions

A series of test foundations monitored during a subsidence event in 1990 were left with permanent tilt, curvature, and substantial cracking. The foundations were releveled in 1991 using Atlas Systems continuous lift piers. The continuous lift piers removed the tilt and curvature and significantly reduced the width of the foundation cracks. In a typical residential structure damaged by subsidence, the restoration of the foundation by the continuous lift piers would have corrected most distorted elements such as sticking doors and windows. Since subsidence often occurs relatively slowly, the continuous lift system could have been used to maintain the structure in a level and undistorted state during subsidence, if desired. The Atlas pier system does not strengthen the structure, and as such is not a structural damage mitigation technique. However, the continuous lift piers were found to be an effective functional damage mitigation technique. The system was not detrimental to the foundation response during subsidence, and permits rapid restoration of structural function after subsidence has occurred. If it had been used in conjunction with repairs to strengthen the foundations, the deformations due to the second event could have been reduced.

Acknowledgements

Funding for this project was received from the National Science Foundation Grant No. BCS-8915243, the Illinois Mine Subsidence Insurance Fund, the U.S. Bureau of Mines Twin Cities Research Center, and Old Ben Coal Co. The authors are grateful for this support.

References

Atlas System, Inc. 1990. Atlas Piers foundation underpinning. Technical Guide, Independence, MO.

Bennett, R.M., E.C. Drumm, and G. Lin 1992. Subsidence effects on structures, vol.1 and vol.2. Geotechnol., Univ. TN, Knoxville, Rep. 92-01.

Bhattacharya, A., M.M. Singh, and C.Y. Chen 1984. Proposed criteria for subsidence damage to buildings. p. 747-755. In Proceedings, Twenty-Fifth Symposium on Rock Mechanics, Evanston, IL.

Dyni, R.C. and M. Burnett 1993. Speedy backfilling for old mines. Civil Eng. 63(9): 56-58.

Gray, R.E. 1988. Coal mine subsidence and structures. p. 69-86. In Mine induced subsidence: effects on engineered structures. ASCE Geotech. Spec. Pub. 19.

Kane, W.F., R.M. Bennett, and E.C. Drumm 1990. Construction and instrumentation of test foundations for subsidence damage assessment. p. 311-321. In Proceedings, Third Conference on Ground Control Problems in the Illinois Coal Basin. (Mt. Vernon, IL, August 1990).

Lin, G. 1993. Structural damage mechanisms associated with differential ground movements. Ph.D. Thesis, Univ. TN, Knoxville, p. 270.

Marino, G.G. 1992. Innovative repair of subsidence damage. p. 139-145. In Third International Workshop on Surface Subsidence Due to Underground Mining. Morgantown, WV.

Powell, L.R., T.L. Triplett, and R.E. Yarbrough 1988. Foundation response to high extraction mining in southern Illinois. Bu Mines R1 p. 45.

Walker, J.S. 1987. Foundation response to subsidence induced ground movements. Presented at Appalachian Coal Mining, SME Eastern Regional Meeting, Pittsburgh, PA.