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Estimation of *in situ* viscoelastic parameters of weak floor strata by plate-loading tests

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Summary

This paper explores an approach to estimation of the viscoelastic parameters of weak floor strata using plate-loading tests. Mathematical equations are derived to describe deformation-time history for the standard Burgers model under three-dimensional stress–strain conditions, which are verified with a finite element model. A number of time-dependent in-mine plate-loading tests were conducted and the values of the viscoelastic parameters were estimated based on the derived equation. It is shown that large discrepancies between the parameter values estimated from the plate-loading tests and those acquired from the in-mine convergence data are the results of neglecting adjacent pillar interaction. Finite element modelling was conducted to investigate the effects of adjacent pillar interactions upon the pillar settlement. Based on the finite element analyses, a correction curve was developed to adjust the viscoelastic parameter values to take into account the interaction between adjacent pillars. With the correction, the parameter values estimated from the plate-loading tests compared favourably with those acquired from the in-mine convergence results.

Keywords: Plate–load test, viscoelastic, modelling, weak rock, mine floor

Introduction

In underground coal mines associated with weak floor strata, the characteristics of the floor strata play predominant roles in determining the stability of mine openings. Studies conducted in the Illinois coal basin, where coal seams are typically underlain by 0.5–2 m of weak strata, indicate that the pillar design in room-and-pillar mines at depths less than 120 m is governed by the strength of weak floor strata rather than that of coal (Chugh and Hao, 1990). The mining-induced deformation of weak floor strata frequently manifests itself in the form of floor heave, pillar settlement and surface subsidence. These types of deformation are generally time-dependent (Chugh *et al.*, 1987; Chugh and Hao, 1990). Therefore, estimating the time-dependent properties of the weak floor strata is extremely important for determining long-term pillar settlements, surface subsidence, and stability of longwall supports operating on top of weak floor strata.

Few data are available on the time-dependent properties of weak floor strata. Those from *in situ* time-dependent plate–loading tests are even more limited. An attempt is made in this study to estimate viscoelastic parameters of weak floor strata from in-mine tests. Mathematical equations were derived to describe deformation-time history for the standard Burgers model under three-dimensional stress-strain conditions. The equation was verified using a three-dimensional finite element model developed with ABAQUS on a CRAY supercomputer. A number of time-dependent in-mine plate loading tests were conducted and the values of the viscoelastic parameters were estimated based on the equation derived. The estimated parameter values were compared with those acquired from the in-mine convergence data. The discrepancies were discussed and analysed. Additional finite element modelling was conducted to investigate the effects of adjacent pillar interactions upon the pillar settlement. Based on the finite element analyses, a correction curve was developed to adjust the viscoelastic parameter values to take into account the interaction among adjacent pillars.

Mathematical modelling of the viscoelastic behaviour of the weak floor strata subjected to a three-dimensional stress field

Rheological models have been effectively utilized to describe time-dependent behaviour of geological materials (Hardy *et al.*, 1969; Sheorey and Dunham, 1978; Chugh *et al.*, 1987). Among the four basic models, namely, Maxwell, Kelvin, Ross and Burger's models, the last one is considered to represent most realistically the creep behaviour of mine rocks (Lu and Wright, 1968; Sheorey and Dunham, 1978; Chugh *et al.*, 1987). In this study, the Burgers model with one Kelvin unit, as shown in Fig. 1, was selected to simulate the time-dependent behaviour of the immediate weak floor strata.

The differential equation of the standard Burgers model in one-dimensional form is:

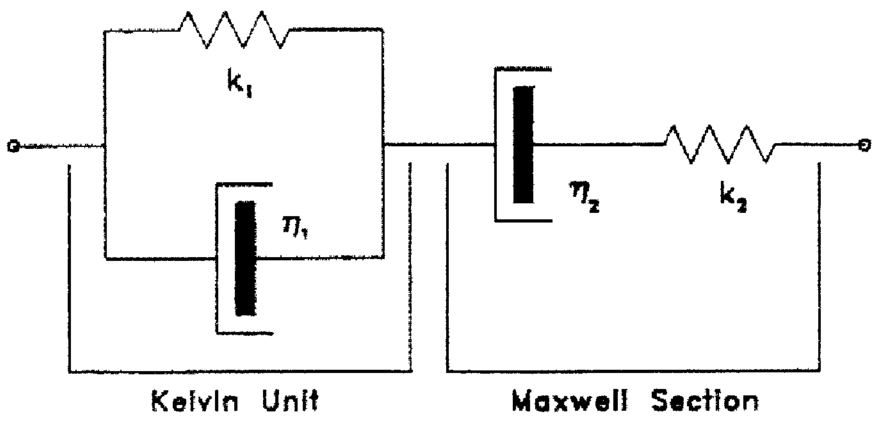

Fig. 1. The standard Burger's model.

$$\eta_1 \varepsilon'' + k_1 \varepsilon' = \frac{\eta_1}{k_2}\sigma'' + \left[1 + \frac{k_1}{k_2} + \frac{\eta_1}{\eta_2}\right]\sigma' + \frac{k_1}{\eta_2}\sigma \tag{1}$$

where ε = strain, σ = stress, k_1, k_2, η_1 and η_2 = viscoelastic parameters of the standard Burger's model, $'$ indicates first differential with respect to time t, and $''$ indicates second differential with respect to time $t_{(2)}$. The solution of Equation 1 is:

$$\varepsilon = \frac{\sigma}{k_2} + \frac{\sigma}{k_1}\left[1 - \exp\left(-\frac{k_1}{\eta_1}t\right)\right] + \frac{\sigma}{\eta_2}t \tag{2}$$

However, a three-dimensional state of stresses and strains exists when conducting plate-loading tests on weak floor strata. Therefore, Equation 2 cannot be directly applied to the plate-loading problem. Additional mathematical operations have to be carried out to take into consideration the three-dimensional stress-strain conditions.

Since the thickness of weak floor strata and the width of mine openings are relatively large compared with the plate size, plate-loading on weak floor strata can be considered as the case of uniformly distributed stresses over a rectangular area on semi-infinite medium. Based on the theory of elasticity, the deformation of the surface of elastic semi-infinite medium under a plate is (Timoshenko and Goodier, 1970):

$$w = \frac{0.95\sigma B(1 - \nu^2)}{E} = \frac{0.95\sigma B}{4}\left(\frac{1}{G} + \frac{3}{3K + G}\right) \tag{3}$$

where w = average displacement under the plate, σ = average stress under the plate, ν = Poisson's ratio, B = width of the plate, E = Young's modulus (modulus of elasticity), G = modulus of rigidity (shear modulus), and K = bulk modulus.

To develop a rheological model of plate–loading on a semi-infinite Burger's solid, the Laplace transformation can be utilized to convert the solution for an elastic medium to that for a viscoelastic medium. This approach has been successfully employed previously by several authors (Bland, 1960; Lu and Wright, 1968; Jaeger and Cook, 1979) and was also employed in this study to obtain a viscoelastic solution of the floor deformation under a plate.

For plate–loading on weak floor strata, when a constant stress is applied on the plate after time 0, the following initial conditions may apply:

$$\sigma_{(t \le 0)} = 0; \quad \sigma_{(t > 0)} = \sigma_0; \quad \sigma'_{(t = 0)} = 0$$

$$\varepsilon_{(t \le 0)} = 0; \quad \varepsilon'_{(t = 0)} = 0 \quad (\text{however, } \varepsilon'_{(t = 0+)} \ne 0)$$

These conditions are necessary for the Laplace transformation. According to Bland (1960), if the dependent variables and the boundary conditions in the elastic solution are replaced by their Laplace transforms and the elastic moduli by the corresponding parameter-varying moduli, then the viscoelastic solution for these variables is obtained by inversion of the expressions so obtained for the transforms of the dependent variables. The viscoelastic solution for the floor deformation under a plate is then derived from the corresponding elastic solution as below.

The viscoelastic stress–strain relation in three-dimensions can be written as:

$$f(D)s_{rs} = 2g(D)e_{rs} \tag{4}$$

$$f_1(D)s = 3g_1(D)e \tag{5}$$

where s_{rs} = stress deviator tensor and r and s may take the values of x, y or z, e_{rs} = strain deviator tensor and r and s may take the values of x, y or z, s = mean normal stress, e = mean normal strain and $f(D)$, $g(D)$, $f_1(D)$ and $g_1(D)$ are polynomials of differential operators having the form suggested by Equation 1 for the Burger's model. The Laplace transforms of the stress–strain relation expressed in Equations 4 and 5 are:

$$f(p)\bar{s}_{rs} = 2g(p)\bar{e}_{rs} \tag{6}$$

$$f_1(p)\bar{s} = 3g_1(p)\bar{e} \tag{7}$$

where p is a real positive number sufficiently large to make the transformation converge. Detailed mathematical operations may be found elsewhere (Bland, 1960; Jaeger and Cook, 1979).

Referring to Equation 1, the following Laplace transform operators are obtained:

$$f(p) = \frac{\eta_1}{k_2}p^2 + \left(1 + \frac{k_1}{k_2} + \frac{\eta_1}{\eta_2}\right)p + \frac{k_1}{\eta_2} \tag{8}$$

$$g(p) = \eta_1 p^2 + k_1 p$$

Using the above operators, two forms of viscoelastic solutions for floor deformation under a plate were developed in this study, based on different assumptions for material behaviour. In the first formulation, the floor material is considered to be elastic in hydrostatic compression and to behave as a Burger's material in distortion. For a given elastic solution, the corresponding viscoelastic solution is obtained by replacing G with $g(p)/f(p)$ and σ with σ_0/p (since $\sigma = \sigma_0$ when $t > 0$), and taking the inverse of the Laplace transform. Following this approach, the Laplace transform of the floor displacement under the plate is derived as:

$$\bar{w} = \frac{0.95\sigma_0 B}{4}\left[\frac{\alpha_1 p^2 + \alpha_2 p + \alpha_3}{\eta_1 p^2 + k_1 p} + \frac{3(\alpha_1 p^2 + \alpha_2 p + \alpha_3)}{3K(\alpha_1 p^2 + \alpha_2 p + \alpha_3) + \eta_1 p^2 + k_1 p}\right] \tag{10}$$

where w = floor displacement under the plate with the overline indicating the Laplace transform of the variable, $\alpha_1 = \eta_1/k_2$, $\alpha_2 = 1 + k_1/k_2 + \eta_1/\eta_2$, and $\alpha_3 = k_1/\eta_2$.

Taking the inverse of the above Laplace transform results in:

$$w = \frac{0.95\sigma_0 B}{4}\left[\frac{k_1 + k_2}{k_1 k_2} + \frac{1}{K} + \frac{t}{\eta_2} - \frac{1}{k_1}\exp\left(-\frac{k_1}{\eta_1}t\right) + \frac{3(\alpha_1 R_1^2 + \alpha_2 R_1 + \alpha_3)}{(3K\alpha_1 + \eta_1)R_1(R_1 - R_2)}\exp(R_1 t) - \frac{3(\alpha_1 R_2^2 + \alpha_2 R_2 + \alpha_3)}{(3K\alpha_1 + \eta_1)R_2(R_1 - R_2)}\exp(R_2 t)\right] \tag{11}$$

where

$$R_1 = \frac{-3K\alpha_2 - k_1 + \sqrt{(3K\alpha_2 + k_1)^2 - 12K\alpha_3(3K\alpha_1 + \eta_1)}}{6K\alpha_1 + 2\eta_1}$$

$$R_2 = \frac{-3K\alpha_2 - k_1 - \sqrt{(3K\alpha_2 + k_1)^2 - 12K\alpha_3(3K\alpha_1 + \eta_1)}}{6K\alpha_1 + 2\eta_1}$$

The solution is obviously in a very complex form and the physical interpretation of the equation is difficult to comprehend.

In order to simplify the solution, the second formulation assumes that the Poisson's ratio of the weak floor strata is a constant and only the Young's modulus is a time-dependent parameter. It then follows that the Young's modulus E in the elastic solution is replaced by the equivalent time-varying modulus and the Laplace transform of the displacement becomes:

$$\bar{w} = 0.95\sigma_0 B(1 - \nu^2)\frac{\frac{\eta_1}{k_2}p^2 + \left(1 + \frac{k_1}{k_2} + \frac{\eta_1}{\eta_2}\right)p + \frac{k_1}{\eta_2}}{p(\eta_1 p^2 + k_1 p)} \tag{12}$$

and taking the inverse of the Laplace transform gives the displacement of the floor underneath the plate as:

$$w = 0.95\sigma_0 B(1 - \nu^2)\left\{\frac{1}{k_2} + \frac{1}{k_1}\left[1 - \exp\left(-\frac{k_1}{\eta_1}t\right)\right] + \frac{t}{\eta_2}\right\} \tag{13}$$

This equation has a form similar to that of Equation 2.

To verify the accuracy of the equation derived under the given assumptions, a three-dimensional finite element model was developed with ABAQUS, a general-purpose finite element modelling software package, on a CRAY supercomputer. The Burger's material property was defined by a user subroutine, which is an option provided by ABAQUS. Since the loading of a square plate on a semi-infinite medium is symmetric about the centre point of the plate, the modelling of one-quarter of the plate and the floor strata is sufficient to represent the plate–loading on the floor. The finite element mesh is illustrated in Fig. 2, which contains 8473 elements and 9808 nodes, representing a quarter of the plate-loading block. The parameter values used in the verification are given in Table 1.

The computer-generated floor displacement under the plate is compared with that predicted by Equation 13 using the same set of parameter values. The results are plotted in Fig. 3. Excellent agreement was achieved between the finite element modelling and Equation 13. It can, therefore, be safely concluded that the assumption made for the mathematical modelling is appropriate and the derivation of Equation 13 is correct.

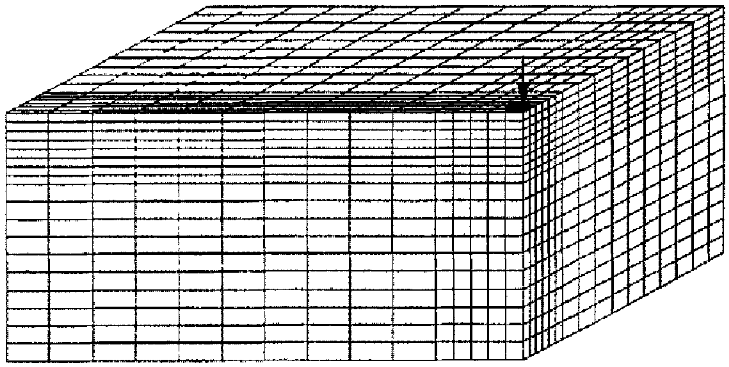

Fig. 2. The three-dimensional finite-element mesh for a plate-loading test block.

Table 1. Parameters used in three-dimensional modelling

Applied stress: σ_0 = 2.41 MPa (350 psi)
Plate size: B = 30.5 cm (12 in)
Poisson's ratio: ν = 0.3
Viscoelastic parameters:
k_1 = 614 MPa (8.9E4 psi)
k_2 = 207 MPa (3.0E4 psi)
η_1 = 1.10E5 MPa-s (1.6E7 psi-s)
η_2 = 6.90E6 MPa-s (1.0E9 psi-s)

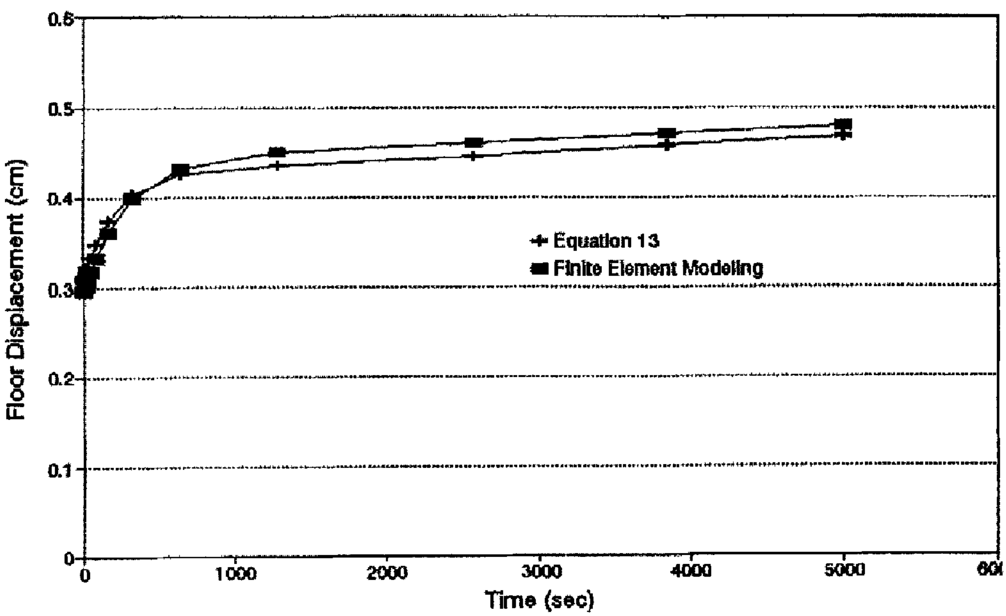

Fig. 3. Comparison of Equation 13 with finite-element modelling.

In situ time-dependent plate–loading tests

A number of time-dependent plate-loading tests were conducted in four Illinois coal mines, in Springfield (No.5) or Herrin (No.6) coal seams. The weak underclay thickness in these mines varies between 0.6 m and 2.1 m (2 ft to 7 ft). Three of the mines employed room-and-pillar mining methods and one used longwall mining methods. The tests were conducted in mining panels 76.2 m to 167.6 m (250 ft to 550 ft) below the surface. In most cases, tests were conducted in relatively freshly mined-out areas and no areas were mined more than 2 weeks earlier.

The tests were performed using an automated microcomputer-based equipment setup developed to determine floor-bearing capacity. This setup, shown in Fig. 4, is capable of providing a maximum load of 1000 kN with a maximum allowable deformation of 5.1 cm (2 in). The setup consists of an automated loading and data acquisition system. A hydraulic jack of 100-ton capacity was utilized to provide the load and the hydraulic pressure was measured with pressure transducer. Rigid square plates ranging from 15.2 cm to 45.7 cm (6 in to 18 in) were used in the tests. The deformation was measured with linear variable differential transformers (LVDT).

The test procedures suggested by ISRM (Brown, 1981) were followed in planning the time-dependent tests. The selected test site was cleaned of all gob material and chipped until a relatively level surface was prepared. A thin layer of plaster was spread on the prepared area before the plate was placed on it and levelled. Incremental loading was applied to the plate during a test. The failure bearing capacity of the floor was reached in two to four load increments. For each increment, the load was held constant with a

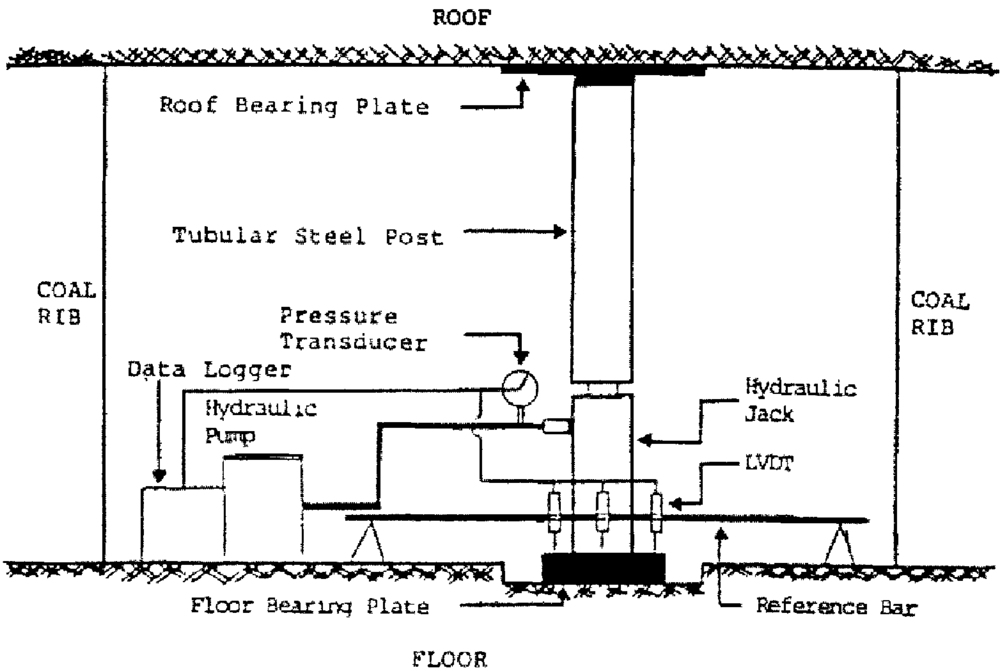

Fig. 4. Plate-loading test setup.

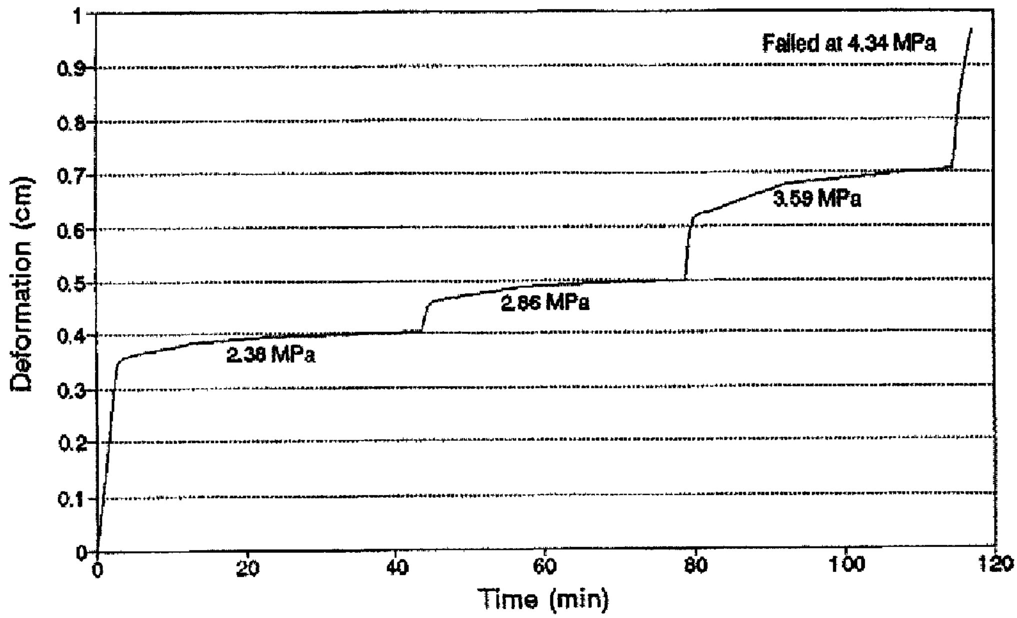

Fig. 5. Floor deformation as a function of time at Mine 1 (30.5 cm square plate).

variation of less than 3%. The deformation was measured by three LVDTs which were mounted on an angle-iron reference beam and set 90° apart on the bearing plate (this is not shown clearly in Fig. 4, which is only a two-dimensional view). Load-deformation data were recorded at time intervals of 5 s for the first 10 min of each increment. The time intervals increased to approximately 10 min afterwards. The duration of each load increment was in the range of 1 to 4 h so that the test could be completed in a reasonable length of time. Tests results indicated that at this length of duration, the deformation had reached the stage of steady deformation with a constant creep rate and complete information had been acquired.

Typical curves of deformation versus time are illustrated in Figs 5 and 6. Figure 5 shows the test results for the weak floor strata below the Springfield seam at a depth of 91.4 m (300 ft). Figure 6 shows similar results for the Herrin seam floor strata at a depth of 106.7 m (350 ft). Based on these curves, the time-dependent deformation of the floor strata can be generally characterized with three basic stages: an instantaneous deformation stage when the load is initially imposed on the floor, a transient stage immediately following the previous one when the deformation rate decreases at an exponential rate, and a steady deformation stage with a constant creep rate. This observation is in general agreement with previous laboratory test results and field observations (Hardy *et al.*, 1969; Sheorey and Dunham, 1978; Chugh *et al.*, 1987).

A non-linear regression procedure was employed to analyse the time-dependent plate-loading test results. Based on Equation 13, the viscoelastic parameters k_1, k_2, η_1 and η_2 were estimated. A typical regression curve and the corresponding test data are shown in Fig. 7, which illustrates that the regression curve fits the test data very well. In all the cases, the coefficient of correlation r is greater than 0.95. This demonstrates that the Burger's model with one Kelvin unit is suitable for modelling the time-dependent

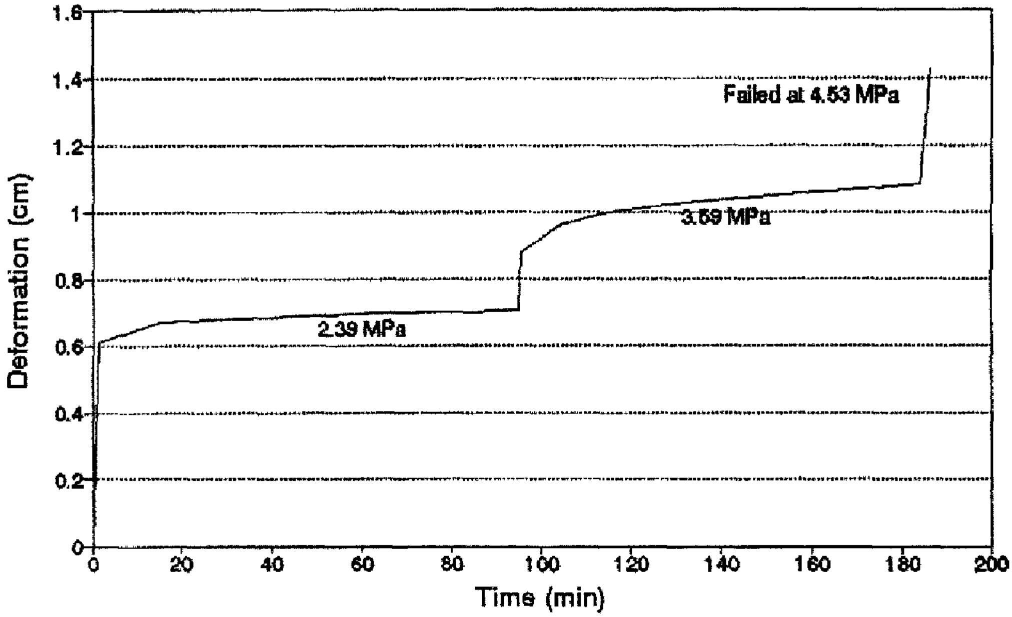

Fig. 6. Floor deformation as a function of time at Mine 2 (30.5 cm square plate).

behaviour of weak floor strata. The estimated parameter values for each time-dependent plate-loading test are listed in Table 2.

Table 2. Viscoelastic parameters of the standard Burger's model estimated from the time-dependent plate-loading tests

Location	σ_0 (MPa)	k_1 (MPa)	k_2 (MPa)	η_1 (MPa-s)	η_2 (MPa-s)
Mine 1	2.39	1450	186	2.00E5	1.03E7
	2.88	290	359	2.90E4	8.28E6
	3.59	207	255	1.66E4	5.03E6
Mine 2					
Site 1	2.39	614	110	1.72E4	2.62E7
	3.59	207	207	1.10E5	6.90E6
Site 2	2.77	1310	228	1.24E6	1.38E7
	3.19	359	96.6	1.86E5	1.79E7
Mine 3					
Site 1	17.6	8280	4900	6.69E6	1.52E8
	23.0	1860	2140	3.79E5	4.41E7
	32.6	2210	3100	3.52E5	8.28E8
Site 2	2.16	255	82.8	1.03E5	3.24E6
	2.70	41.4	55.2	1.66E4	1.03E6
Mine 4	2.88	566	241	4.97E4	2.00E7
	4.07	366	414	1.52E5	8.28E6

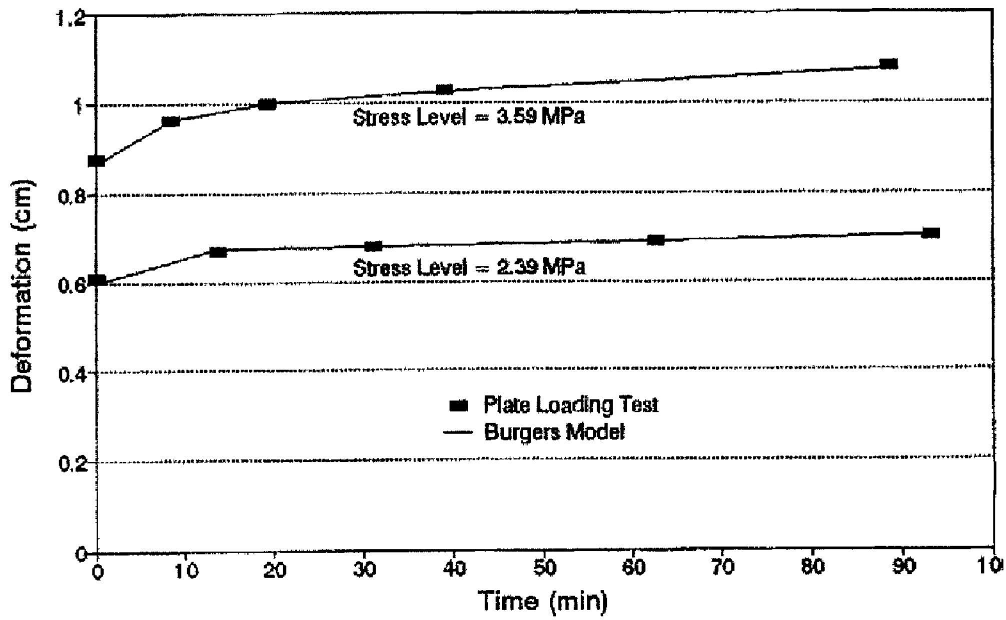

Fig. 7. Comparison of Burger's model with the plate-loading test data.

Comparison of the estimates of parameter values from plate-loading tests with laboratory creep experiments and field observations of pillar settlements

Laboratory creep experiments

Laboratory studies of the time-dependent behaviour of immediate floor strata of Mine 2 were conducted in a previous study (Chugh *et al.*, 1987). Creep tests were performed on core samples taken from the floor strata. Incremental loads were applied and the total duration of the tests on individual samples varied from 18 to 400 h. The Burger's model was also utilized to fit the test data and viscoelastic parameters were estimated. The results are summarized in Table 3, which shows the mean values of the standard Burger's model parameter values for stress levels varying from 40% to 80% of the unconfined compressive strength.

Table 3. Viscoelastic parameters of the standard Burger's model estimated from laboratory creep experiments from Mine 2

Location	k_1 (MPa)	k_2 (MPa)	η_1 (MPa-s)	η_2 (MPa-s)
East section	4070	1380	2.69E6	6.57E8
West section	8070	3660	4.48E6	3.14E8

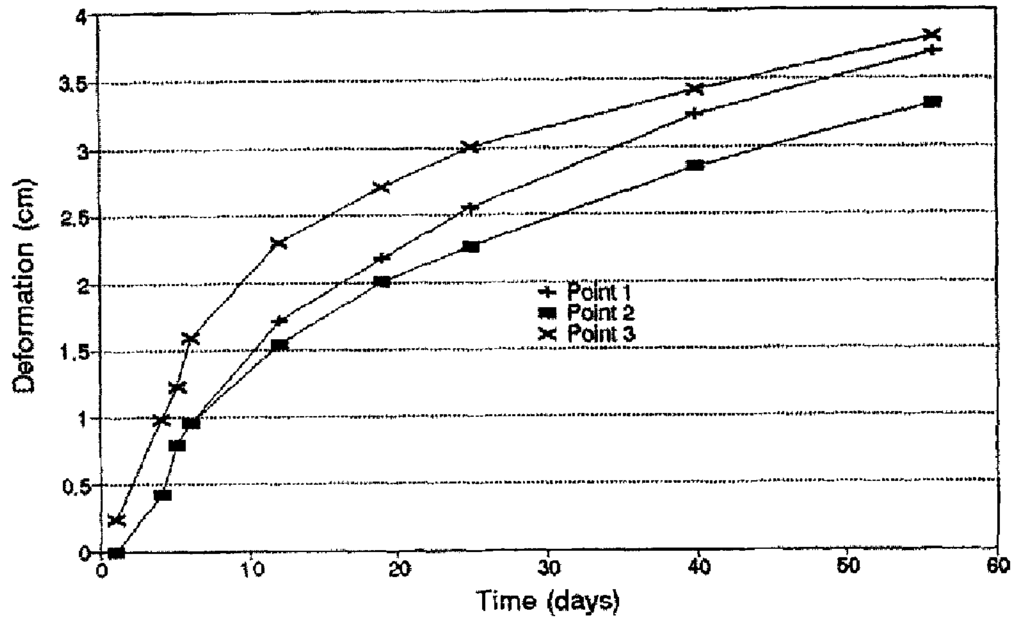

Fig. 8. Typical convergence curves at Site 1, Mine 2.

In-mine convergence data

Underground monitoring of roof–floor convergence was conducted at Site 1 in Mine 2. The thickness of the weak floor strata at this site is about 0.6 m to 0.9 m (2 ft to 3 ft) and the pillar size was 16.8 m by 21.3 m (55 ft by 70 ft) solid. Typical convergence curves are shown in Fig. 8. Since the convergence points could only be installed after the opening was developed, no complete information on the instantaneous pillar settlement due to pillar development could be obtained. The convergence measurements are considered mainly from the transient stage and steady-stage deformation. Based on data gathered, it was concluded that the majority of the convergence was related to pillar settlement rather than due to roof sag. The approximate relation between the pillar settlement and the roof-floor convergence may be expressed as (Chugh and Hao, 1990):

$$S_p = \frac{0.5C\,e}{1 - e} \qquad (14)$$

where S_p = pillar settlement, C = roof–floor convergence at the centre of entry, and e = extraction ratio.

Based on Equation 14, the measurements of roof-floor convergence were converted to pillar settlements. The standard Burger's model was again used to fit the pillar settlement data as a function of time. Typical field data and the regression curve are shown in Fig. 9, which indicates an excellent fit. The viscoelastic parameter values estimated from the pillar settlement data are listed in Table 3.

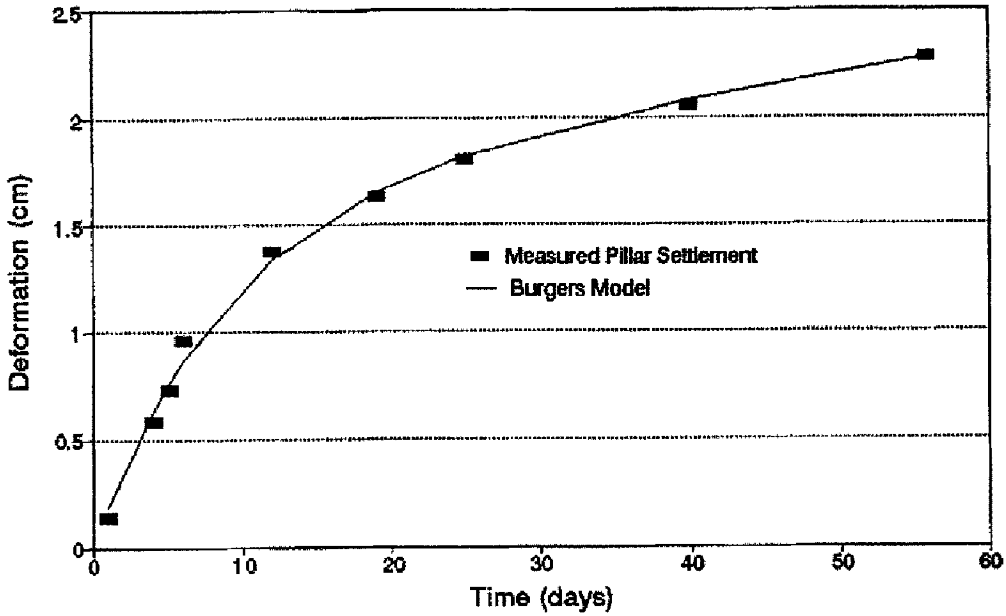

Fig. 9. Comparison of Burger's model with in-mine pillar settlement data.

Comparisons and discussions

The k_1 values estimated from the laboratory data (Table 3) are significantly higher than those from the plate-loading tests (Table 2) and field observations (Table 4). While the values of k_1 from the plate-loading tests are slightly higher than those estimated from field observations, they are in the same range. The parameter k_2 may be interpolated approximately as the instantaneous elastic modulus of the floor material. Since the plate-loading tests were performed directly on the floor strata with little or no disturbance, which is a widely accepted procedure to measure the *in situ* elastic parameters of rock masses, the elastic modulus acquired should be a good representation of the elastic property of the floor strata. This judgment is supported by a previous study (Pytel *et al.*, 1988). It may then be concluded that the short-term time-dependent plate loading tests provide reasonable estimates of the elastic parameters of k_1 and k_2 of the standard Burger's model.

The plate-loading tests give significantly lower values of viscosity parameters η_1 and η_2 than those estimated from the field observations. The parameter values in Table 2 will overpredict the pillar settlement, especially over a long period of time and underestimate the length of the transient time period. Further analysis indicates that a number of

Table 4. Viscoelastic parameters estimated from in-mine pillar settlements of Site 1, Mine 2

Location	k_1 (MPa)	η_1 (MPa-s)	η_2 (MPa-s)
Convg. Pt. 1	131	1.83E8	5.86E8
Convg. Pt. 2	152	2.12E8	6.21E8
Convg. Pt. 3	89.7	1.26E8	8.97E8

important factors were neglected, which contributes to the large discrepancies between the two sets of values. Discussions are presented below to explain the factors affecting the time-dependent behaviour of weak floor strata.

(1) When the plate loading tests were conducted, the entire load was placed on the plate almost instantly. Unlike the plate-loading tests, however, when a mine opening is developed, the load increments on pillars due to excavation is imposed gradually. The loading process will not be completed until the face of the excavation is a certain distance away. In addition, the lowering of the overlying rock strata will not occur immediately and may take several days or weeks to reach a stable condition. Further manifestation of this phenomenon can be found in the form of delayed subsidence on the surface. It typically takes several days or weeks to reach the maximum subsidence after the completion of a underground mine panel. This slow loading process significantly increases the transient stage of floor deformation and when the deformation as a function of time is simulated with the Burger's model, a very large η_1 value will be required. In order to correct η_1 values estimated from plate loading tests for the purpose of predicting pillar settlements, the characteristics of overlying rock strata should be considered and the speed of excavation taken into account.

(2) When predicting the long-term pillar settlement, the viscosity parameter η_2 is more critical. However, the values of η_2 estimated from the field observation are about 10 to 20 times larger than those acquired from the plate-loading tests. In general, the plate-loading tests were conducted in underground openings. The size of the plate is very small compared to the width of an opening and the adjacent load interaction is minimal. In the case of pillar loading on the floor, the pillar size is larger than that of the opening and significant adjacent pillar interactions will occur. Analysis indicates that the value of η_2 is a function of the room to pillar ratio. This relationship was explored using the finite element modelling technique and a correction curve for η_2, to take into account the effects of adjacent pillar interaction, was developed, as presented in the following section.

Finite element modelling of adjacent pillar interactions

Both the plate-loading test and computer modelling exhibited floor heave around the plate, as shown in Fig. 10. By intuitive judgement, if an adjacent load prevents the heave around the plate, the rate of the time-dependent floor displacement under the plate will decrease, resulting in a higher value of η_2. In addition, the gap between the adjacent load and the plate will affect the rate of displacement. The larger the gap is, the less interaction there will be, and vice versa.

In order to investigate the adjacent pillar interactions, a two-dimensional finite element model was developed with ABAQUS as shown in Fig. 11. In most underground mine panels, rectangular pillars are employed and the width of the opening is usually much smaller than that of the pillar. Therefore, a two-dimensional model with a plain strain condition is an adequate approximation of the room and pillar system, especially when studying the pillar interactions along the longer side of rectangular pillars. The two-dimensional model is considered to represent a section across the mid-point of the pillar.

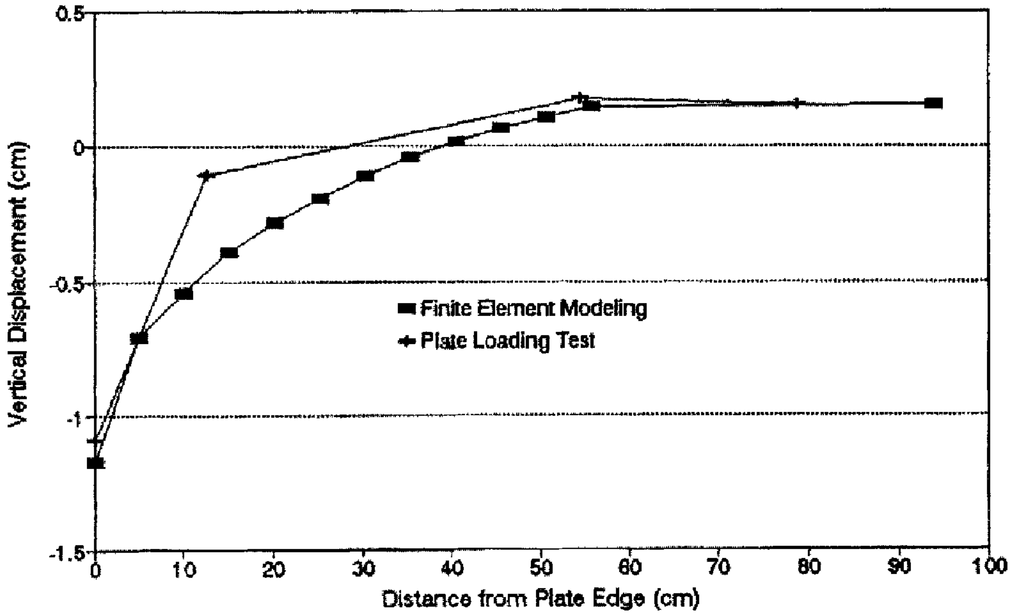

Fig. 10. Floor heave around the plate (60.1 cm square plate).

With the room-to-pillar ratio varied from 0.08 to 7.2, the floor deformation was computed. With each fixed room-to-pillar ratio, the curve of deformation as a function of time was fitted using the Burger's model and a η_2 value was calculated. Each of these η_2 values was then compared with that estimated from the deformation with no adjacent pillar load. The modelling results demonstrated that when the room is small or the pillars are close together, the effect of adjacent pillar interaction is very significant. The η_2 value estimated from the floor deformation with a room-to-pillar ratio of 0.08 may differ as much as 60 times from that estimated from the floor deformation with no adjacent pillar load.

Based on the finite element modelling study, a correction curve has been developed, as shown in Fig. 12. The horizontal axis indicates the room-to-pillar ratio and the vertical

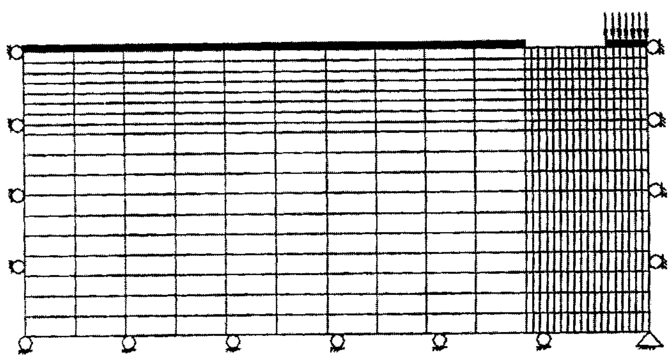

Fig. 11. The two-dimensional finite-element mesh for pillar loading with adjacent surcharge.

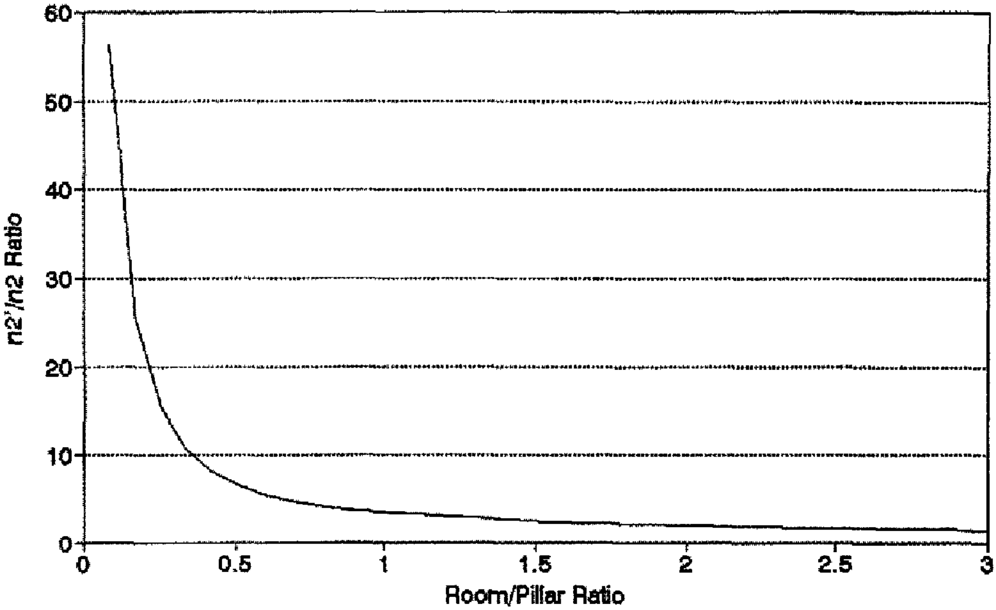

Fig. 12. Correction curve for viscosity parameter η_2.

axis gives the ratio of η_2' to η_2, where η_2' is the viscosity value estimated from the floor deformation with room-to-pillar ratio as indicated on the horizontal axis and η_2 is the viscosity value estimated from the floor deformation with no adjacent load. The curve illustrates that the η_2' to η_2 ratio is high when the room-to-pillar ratio is small and decreases exponentially as the ratio increases. The ratio of η_2' to η_2 stabilizes around the point of the room-to-pillar ratio of 2, indicating negligible pillar interaction when the room-to-pillar ratio is greater than 2.

The correction curve was applied to the *in situ* time-dependent plate-loading test data to obtain η_2' values for the prediction of pillar settlement. Since the plate-loading tests were performed in large openings compared with the plate size, the tests can be considered as being conducted with no effect from adjacent pillar load. The mine pillars have a width

Table 5. Corrected values of the viscosity parameter η_2'

Location	η_2' (MPa-sec)	Location	η_2' (MPa-sec)
Mine 1	1.59E8	Mine 3	
	1.24E8	Site 1	2.14E9
	7.59E7		6.21E8
			1.17E9
Mine 2			
Site 1	3.66E8	Site 2	4.55E7
	9.66E7		1.45E7
Site 2	1.93E8	Mine 4	3.03E8
	2.48E8		1.24E8

ranging from 16.8 m to 21.3 m (55 ft to 70 ft) and openings from 4.6 m to 5.5 m (15 ft to 18 ft). The room-to-pillar ratio is about 0.25 to 0.27. Therefore, correction factors as suggested by Fig. 12 should be applied. The corrected values of the viscosity parameter η_2' were calculated and are presented in Table 5. As compared with those values estimated from Mine 2 convergence data (Table 4), the corrected values are now in a very narrow range, indicating that with proper correction, the η_2 values estimated from the time-dependent plate-loading tests can be used in predicting pillar settlement with reasonable accuracy.

Concluding remarks

This paper has demonstrated a possible approach to estimate the *in situ* viscoelastic parameters of weak floor strata from time-dependent plate-loading tests. Based on *in situ* testing, in-mine convergence monitoring and mathematical and computer modelling, the following conclusions may be drawn:

(1) The standard Burger's model is a good representation of weak floor strata creep properties. The mathematical modelling and the verification by finite element simulation demonstrate that the equation derived for the time-dependent floor displacement under the plate subjected to three-dimensional stress field is an accurate model.
(2) In the laboratory, suitable samples for creep studies can only be obtained from relatively competent rock strata and the size of the specimens is very limited. The results, therefore, represent only the properties of the relatively competent rock strata. Plate-loading tests can be conducted in the mine field with minimal disturbance of the weak floor strata. The parameter values estimated should be closer to that of actual rock masses.
(3) The plate-loading tests provide reasonable estimates of the elastic parameters (k_1 and k_2) of the Burger's model for the weak floor strata.
(4) The plate-loading tests give significantly lower values of viscosity parameters η_1 than those estimated from in-mine convergence measurements. Two factors may have contributed to this difference, namely the slow loading process of overlying rock strata and the limited speed of excavation. In order to correct η_1 values estimated from plate-loading tests for the purpose of predicting pillar settlements, the characteristics of overlying rock strata should be considered and the speed of excavation taken into account.
(5) When predicting the long-term pillar settlement, the viscosity parameter η_2 is more critical. The values of η_2 estimated from the in-mine convergence measurements, however, are about 10 to 20 times larger than those acquired from the plate-loading tests. Analyses indicated that the long-term pillar settlement is significantly affected by the adjacent pillar interactions. Based on finite element modelling studies which took into account the adjacent pillar interactions, a correction curve has been developed. With a proper correction, the η_2 value estimated from the plate-loading tests can be used to predict the long-term time-dependent pillar settlement with reasonable accuracy.

In general, the study has demonstrated that the *in situ* time-dependent plate-loading test is a powerful tool. If used properly, this test can be very effective in determining *in situ* viscoelastic parameters of weak floor strata.

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