Behaviour of suspended shaft-steelwork towers

by G.J. Krige*

Synopsis

The extent of ground movements and stress concentrations in the vicinity of the reef in the deep mine-shafts used in the South African gold-mining industry have led to the requirement that special tower structures be developed to span the reef intersection zone in several new shafts. So that structural engineers are able to design these towers, it is necessary to model the dynamic behaviour of conveyances traversing them in some way, to provide a means to determine the magnitude of the forces generated. This paper describes the development of two such procedures. The first is a numerical method, utilizing a step-by-step integration technique to track the motion of a conveyance through a tower. This technique has been implemented in a computer program, and some results are given.

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Introduction

The ground movements and stress concentrations in the vicinity of the reef in the deep mine-shafts used in the South African gold-mining industry, and the need for earlier extraction of gold to offset the large capital outlay, have led to early extraction of the shaft pillar, in some cases even prior to sinking of the shaft. Hymers[1] describes the problems encountered, and the engineering solutions used, in a number of shafts where pillars were extracted late in the life of the mine or quite early. He quotes a vertical closure at the reef of 1300 mm without backfill, or 650 mm with a soft backfill. Vertical movement figures quoted at 40 m above the reef show a vertical strain of about 1,0 $m\varepsilon$ when no backfill was used, and 0,5 $m\varepsilon$ with soft backfill. For 50 to 100 m above and below the reef intersection at the new South Deep Gold Mine, Valente[2] predicts additional vertical strains of up to 1,3 $m\varepsilon$ and additional lateral strains of 0,6 $m\varepsilon$ after the initial strains following the removal of the shaft pillar and subsequent sinking of the shaft. Referring to shaft pillar removal at the No. 5 Sub Shaft of West Driefontein Gold Mine, Bruce and Stilwell[3] quote vertical strain figures of 0,8 $m\varepsilon$ from 30 to 100 m above, and from 50 to 200 m below, the reef intersection.

The guide-tower concept

Rock strains in the vicinity of the shaft will strain the shaft steelwork and any other equipment in the shaft. The normal arrangement, of fixing shaft steelwork into the shaft lining at regular intervals of 4,5 to 6 m, does not cater for strains as large as those quoted. For many years, a variety of retrofit solutions have been applied by various mines when the shaft pillar is removed. A number of examples are given by Hymers[1]. These measures are very maintenance-intensive, and in some cases have required a reduction in hoisting speeds to ensure satisfactory performance.

It has therefore been proposed (Krige and Devy[4,5], Krige *et al.*[6], Hymers[1]) that initial planning of deep mine-shafts should make provision for a 'shaft tower', a length of shaft steelwork that is supported at some distance above and below the reef intersection, and which is completely isolated from the shaft lining where it passes through the reef. Such towers may be from a minimum of about 30 m long up to a maximum of well over 100 m, depending on the likely magnitude and distribution of the rock strains. Towers may be either braced to act as space trusses, or unbraced to act as space vierendeel girders.

DISCHANG computer model

A conveyance moving through a portion of shaft steelwork that is isolated from the shaft walls generates lateral dynamic behaviour in the tower and the conveyance, which must be modelled in some way. This can be done in a simplified analytical way, or numerically by means of a dynamic analysis program. Two factors combine to eliminate the use of conventional, commercially available programs. The first factor is that the dynamic behaviour is induced by the non-vertical shape of the conveyance guides, rather than by any externally applied force. This non-vertical shape is caused by the shear strain and movements of the ground, and by small misalignments within the tower structure itself. The second factor is that the conveyance is moving through the tower, so that the structure for which the dynamic behaviour is desired is constantly changing. A new program, called 'DISCHANG', was purpose-written for modelling the dynamic behaviour of the tower as it is traversed by the conveyance. The layout of the DISCHANG model is shown schematically in Figure 1.

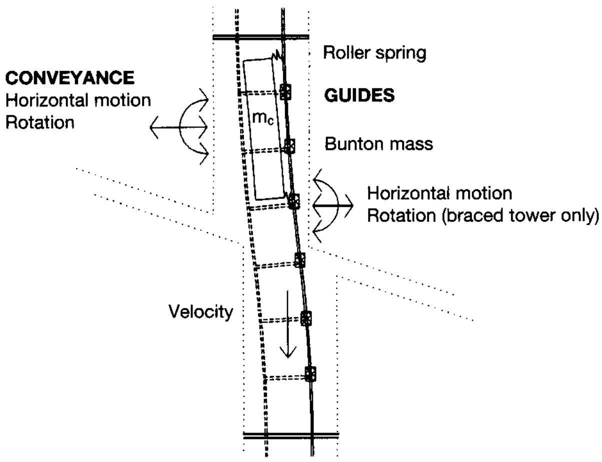

Figure 1—Schematic layout of the DISCHANG model

The second procedure is a simplified analytical method, which considers the shape of the tower as an effective base motion applied to the conveyance. From this procedure, an equation is derived that gives the minimum tower length and the minimum second moment of area that are required to ensure satisfactory operation of the shaft. Finally, an appropriate design procedure for the main parameters of a tower is outlined.

Stiffness and mass matrices

The stiffness and mass matrices are developed in two parts. The first part comprises the stiffness and mass of the tower alone, in the absence of the conveyance. This portion of the matrices remains unchanged throughout the analysis, since there is no change in the tower structure as it is traversed by the conveyance. A lumped mass formulation is used throughout for the mass matrices. With reference to the layout of the tower (Figure 1), the matrices for the tower are:

$$M_t = \begin{vmatrix} 0 & 0 & 0 & 0 & 0 & 0 & . \\ 0 & 0 & 0 & 0 & 0 & 0 & . \\ 0 & 0 & m_b & 0 & 0 & 0 & . \\ 0 & 0 & 0 & mi_b & 0 & 0 & . \\ 0 & 0 & 0 & 0 & m_b & 0 & . \\ 0 & 0 & 0 & 0 & 0 & mi_b & . \\ . & . & . & . & . & . & . \end{vmatrix} \qquad [1]$$

$$K_t = \begin{vmatrix} 0 & 0 & 0 & 0 & 0 & 0 & . \\ 0 & 0 & 0 & 0 & 0 & 0 & . \\ 0 & 0 & \frac{24EI_x}{a^3} & \frac{6EI_x}{a^2} & \frac{-12EI_x}{a^3} & \frac{6EI_x}{a^2} & . \\ 0 & 0 & \frac{6EI_x}{a^2} & \frac{8EI_x}{a} & 0 & \frac{2EI_x}{a^2} & . \\ 0 & 0 & \frac{-12EI_x}{a^3} & 0 & \frac{24EI_x}{a^2} & 0 & . \\ 0 & 0 & \frac{6EI_x}{a^2} & \frac{2EI_x}{a} & 0 & \frac{8EI_x}{a} & . \\ . & . & . & . & . & . & . \end{vmatrix} \qquad [2]$$

where m_b is the mass of a bunton set and associated guides
mi_b is the rotational mass inertia of a bunton set
a is the bunton spacing
E is the elastic modulus of the tower material, and
I_x is the second moment of area of the tower.

The alternate rows and columns of these matrices apply to lateral displacement and rotation of the bunton masses. The rotational terms are ignored when modelling an unbraced tower.

The second portion of the stiffness and mass matrices relates to the conveyance. The additional mass matrix is simply composed of the mass and rotational mass inertia of the conveyance, assuming that the conveyance can be modelled as a rigid body. The additional stiffness matrix varies as the conveyance moves along the tower, as shown in equations [3] and [4]. The mass matrix does not change, but the elements of the stiffness matrix vary, depending on the distance along the guide, and on which buntons support the particular guide against which the rollers are currently running.

$$M_c = \begin{vmatrix} m_c & 0 & 0 & . \\ 0 & mi_c & 0 & . \\ 0 & 0 & 0 & . \\ . & . & . & . \end{vmatrix} \qquad [3]$$

$$K_c = \begin{vmatrix} k_l & 0 & -\alpha k_l & 0 & -\beta k_l & 0 & -\eta k_l & 0 & \zeta k_l & 0 & . \\ 0 & k_r & -\alpha k_r & 0 & -\beta k_l & 0 & -\eta k_r & 0 & \zeta k_r & 0 & . \\ -\alpha k_l & -\alpha k_r & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & . \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & . \\ -\beta k_l & -\beta k_r & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & . \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & . \\ -\eta k_l & -\eta k_r & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & . \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & . \\ -\zeta k_l & \zeta k_r & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & . \\ . & . & . & . & . & . & . & . & . & . & . \end{vmatrix} \qquad [4]$$

where m_c is the conveyance mass
mi_c is the rotational mass inertia of the conveyance
k_l is the stiffness against lateral motion of the conveyance
k_r is the stiffness against rotational motion of the conveyance
α, β, ζ, and η are factors for conveyance position along guide.

In equation [4], the lateral stiffness, k_l, and the rotational stiffness, k_r, of the conveyance are calculated from the roller stiffness combined with the guide stiffness at the roller position or, if the roller spring has been fully compressed, from the guide stiffness only. The factors α, β, ζ, and η are based on the position of the roller along a guide span, which defines the distribution of the roller or slipper force to the buntons immediately above and below it. The terms containing these factors are moved across the columns of the stiffness matrix, and down the rows, as the conveyance moves through the tower.

In order to allow for the initial shape of the tower which comprises the curvature necessary to negotiate the shear displacement across the reef and a random misalignment component, without having initial forces that would influence the dynamic behaviour of the tower, an initial equivalent force vector is calculated from

$$\boldsymbol{M}_t\ddot{\boldsymbol{x}} + \boldsymbol{K}_t\boldsymbol{x} = \boldsymbol{F}_{t0}, \qquad [5]$$

where x is the lateral and rotational displacement vector.

(The normal mathematical notation is used, in which a dot over a symbol indicates differentiation with respect to time, and bold type indicates matrices or vectors.)

If the tower is assumed to be at rest before the conveyance enters it, the initial accelerations are zero. The initial tower force vector is thus

$$\boldsymbol{F}_{t0} = \boldsymbol{K}_t\boldsymbol{x}. \qquad [6]$$

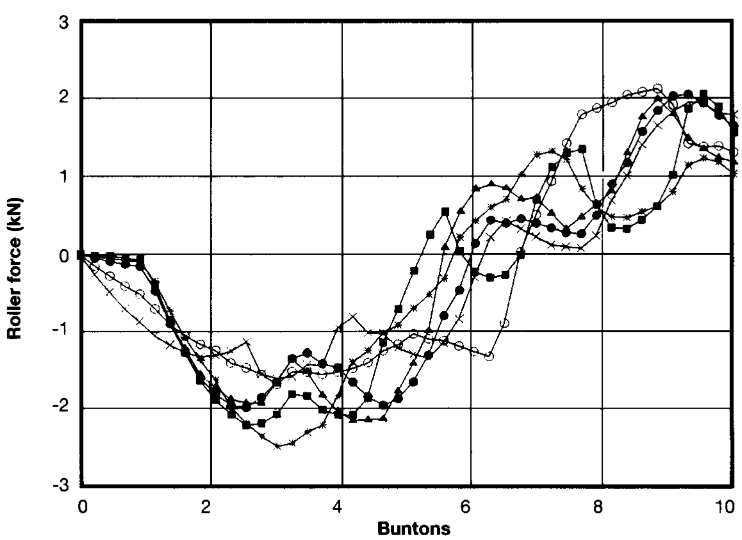

Figure 2—Roller forces during six model runs

Figure 3—Average roller forces during six model runs

The complete equation of motion of the tower is then:

$$(\boldsymbol{M}_t + \boldsymbol{M}_c)\ddot{\boldsymbol{x}} + (\boldsymbol{K}_t + \boldsymbol{K}_c)\boldsymbol{x} = \boldsymbol{F}_{t0}. \qquad [7]$$

Parametric and analytical study of behaviour

The DISCHANG program was used to carry out a parametric study of the dynamic behaviour of suspended shaft-steelwork towers. In the initial study, the parameters listed in Table I were used, and multiple runs were carried out to establish the influence of the small construction misalignments defined within the tower.

Two different tower lengths were used for this study, 54 m and 30 m. The longer tower gave very few slipper contact events, while in the shorter tower, slipper contact occurred during every run. Slipper contact is the term used to describe an occasion when the magnitude of the force is sufficient to push the roller back, and allow the slipper to come into contact with the guide.

Behaviour without slipper contact

The sum of the roller forces on all four rollers for the longer tower is shown in Figure 2 for six of the runs. The average force for these six runs is shown in Figure 3.

Much of the time, the leading roller on one side provides most of the total force. It can thus be assumed that the force shown in Figure 3 approximately represents the force on one roller only.

The behaviour of the conveyance in the tower can be treated as a base motion problem, the shape of the tower defining the base motion. If it is assumed that the shape of the tower approximates the first half of a cosine curve, then the position, velocity, and acceleration of the base are the values which can be defined for the S-shaped tower, i.e.:

$$x_t = \frac{S_t}{2}\left[1 - \cos(\omega_t t)\right]$$
$$\dot{x}_t = \frac{S_t\omega_t}{2}\sin(\omega_t t) \qquad [8]$$
$$\ddot{x}_t = \frac{S_t\omega_t^2}{2}\cos(\omega_t t),$$

where S_t is the shear deformation of the tower.

Table I

Tower and conveyance parameters

Item	Value	Item	Value
Bunton mass	12,5 t	Conveyance mass	43 t
Conveyance length	14 m	Hoisting velocity	18 m/s
Bunton space	6 m	Bunton stiffness	7500 kN/m
Tower stiffness	$10^4 \times 10^{-6}$ m^4	Guide inertia	28×10^{-6} m^4
Roller stiffness	250 kN/m	Tower misalignment	0,003 m
Shear displacement	0,08 m	Damping ratio	3%
Roller stroke	0,01 m		

In these equations, the time taken for the conveyance to traverse the tower is T_t, and the period of the tower shape is twice this value. Therefore

$$T_t = \frac{L_t + L_c}{V}.$$

$$\therefore \omega_t = \frac{2\pi}{2T_t} = \frac{\pi V}{L_t + L_c}, \qquad [9]$$

where L_t is the length of the tower,
L_c is the length of the conveyance, and
V is the hoisting velocity

The equation of motion for the conveyance is

$$m_c\ddot{x}_c + k_c x_c = -m_c\ddot{x}_t \qquad [10]$$

where k_c is the combined stiffness of the conveyance and the guide tower, and
x_c is the relative displacement between the conveyance and the initial position of the guide tower.

The solution to equation [10], given by Warburton[7], is

$$x_c = e^{-\gamma\omega_n t}\left[A_1\sin(\omega_n t) + A_2\cos(\omega_n t)\right] - \frac{\frac{S_t r^2}{2}\cos(\omega_t t - \alpha)}{\sqrt{\left(1-r^2\right)^2 + (2\gamma r)^2}}, \qquad [11]$$

where r is the frequency ratio, ω_t/ω_n,
ω_n is the natural frequency of the conveyance, and
α is the phase angle.

With low damping, it can be assumed that $e^{\gamma\omega t} \approx 1$, and that the damping term $(2\gamma r)^2 \approx 0$. Also, for $r < 1$, $\alpha \approx 0$, and for $r > 1$, $\alpha \approx \pi$. Equation [11] can thus be written as

$$x_c = A_1\sin(\omega_n t) + A_2\cos(\omega_n t) - \frac{S_t r^2}{2\left(1-r^2\right)}\cos(\omega_t t). \qquad [12]$$

Applying the boundary conditions of zero relative displacement, and zero relative velocity at the beginning of the tower, it can be shown that the constants in equation [12] are

$$A_1 = 0$$

$$A_2 = \frac{S_t r^2}{2\left(1-r^2\right)}. \qquad [13]$$

We thus have that the displacement of the conveyance relative to the tower, and the force between them, are:

$$x_c = \frac{S_t}{2\left(1/r^2 - 1\right)}\left[\cos(\omega_n t) - \cos(\omega_t t)\right]$$

$$F_c = k_c x_c = \frac{k_c S_t}{2\left(1/r^2 - 1\right)}\left[\cos(\omega_n t) - \cos(\omega_t t)\right]. \qquad [14]$$

It can be seen that this equation for the relative displacement is a function of the tower shear displacement and the frequencies only. The natural frequency of the conveyance depends primarily on the mass of the conveyance and the stiffness of the rollers, and for a flexible tower, the stiffness of the tower. However, the stiffness of the buntons and the guides, and the time during which only one end of the conveyance is within the tower, also influence the effective stiffness. Calculation of the frequency on the basis of the conveyance mass with two rollers active, and the central tower stiffness, gives

$$\frac{1}{\omega_n} = \sqrt{m_c\left(\frac{1}{2k_s} + \frac{L_t^3}{192EI_x}\right)}, \qquad [15]$$

where k_s is the stiffness of the roller spring.

This should be reduced by an amount that varies, depending on the other flexibility. The reduction is difficult to calculate, and perhaps needs a more detailed assessment, but in the current example, it appears that it can be taken to be approximately one-third. Figure 4 shows the results from equation [14], for a natural frequency of 3,4 rad/s from equation [15], and a frequency of two-thirds of this, i.e. 2,2 rad/s. It can be seen that the form of the curve for 2,2 rad/s closely resembles the force curve predicted by DISCHANG in Figure 3, although the force magnitude is somewhat higher.

In equation [14], it can be seen that the relative displacement is the tower shear multiplied by a function of the frequencies. Calculating the maximum values of the frequency function (i.e. displacement divided by tower shear), and plotting these against the frequency ratio, gives the curve shown in Figure 5. The relative displacement values in Figure 5 are independent of the actual frequencies. The end relative displacement depends on the actual frequencies, but the general trend shown remains correct.

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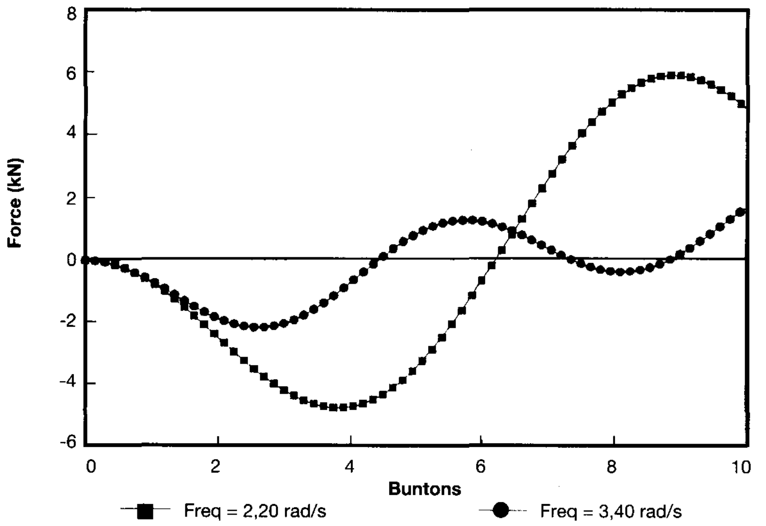

Figure 4—Forces predicted along tower length

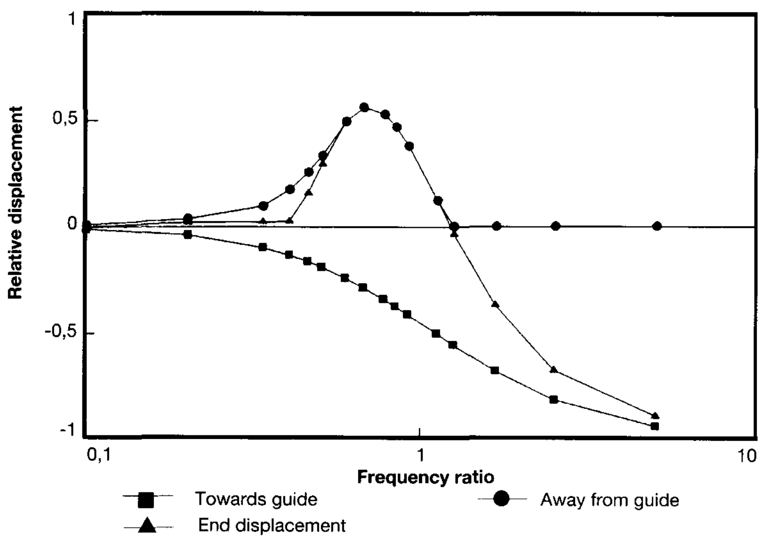

Figure 5—Tower displacement ratio and end displacement

High positive or negative values of displacement indicate that slipper contact will occur, and a high end displacement indicates that a very high slamming force will be induced as the conveyance leaves the tower. It is thus clear from the results shown in Figure 5 that the frequency ratio should be less than about 0,4 if the tower is to operate adequately for the normal roller spring stroke of about 10 to 15 mm.

Behaviour with slipper contact

Using the conveyance parameters in Table I, the COMRO guidelines developed by Thomas[8] predict that the slipper force caused by slamming on misaligned shaft steelwork will be

$$F_s = 1980e \text{ kN}, \qquad [16]$$

where e is the guide misalignment in metres. This is taken to be the maximum value at the centre of the curved shape taken up by the tower, which can be shown to be:

$$e = \frac{3aS_t}{2L_t}$$

$$= \frac{3S_t}{2(N+1)} \quad \text{for a braced tower, and}$$

$$e = \frac{S_t}{N+1} \quad \text{for an unbraced tower,} \qquad [17]$$

where N is the number of buntons in the tower.

Using this maximum misalignment within the guide tower, the slamming force is as shown in Figure 6. A series of DISCHANG runs were carried out using the basic parameters shown in Table I, but with differing values for the tower second moment of area, I_x. The resulting maximum slipper forces are also shown in Figure 6.

Two influences can be seen in figure 6, one for stiff towers, and one for flexible towers. In the case of stiff towers, where the second moment of area is 10 000 x 10^{-6} m^4 or more, it can be seen that the slipper forces follow a trend similar to the slamming forces, but reduce to zero in the longer towers. The slamming force predicted by Thomas[8] in the COMRO guidelines may be modified to allow for the influence of the central flexibility of the tower. Recognizing that the tower behaves as a fixed-ended beam, the central stiffness of the tower may be taken as

$$\frac{1}{K_t} = \frac{L_t^3}{192EI_x}. \qquad [18]$$

The bunton stiffness may then be modified as suggested by Thomas[8] for conveyance flexibility, to give

$$\frac{1}{K_b'} = \frac{1}{K_t} + \frac{1}{K_b} = \frac{L_t^3}{192EI_x} + \frac{1}{K_b}. \qquad [19]$$

For varying tower lengths, the slamming force predicted by the COMRO guidelines can then be shown to be as given in Table II. Figure 6 shows that these forces are up to 40 per cent higher than those predicted by DISCHANG, but generally give a good upperbound value.

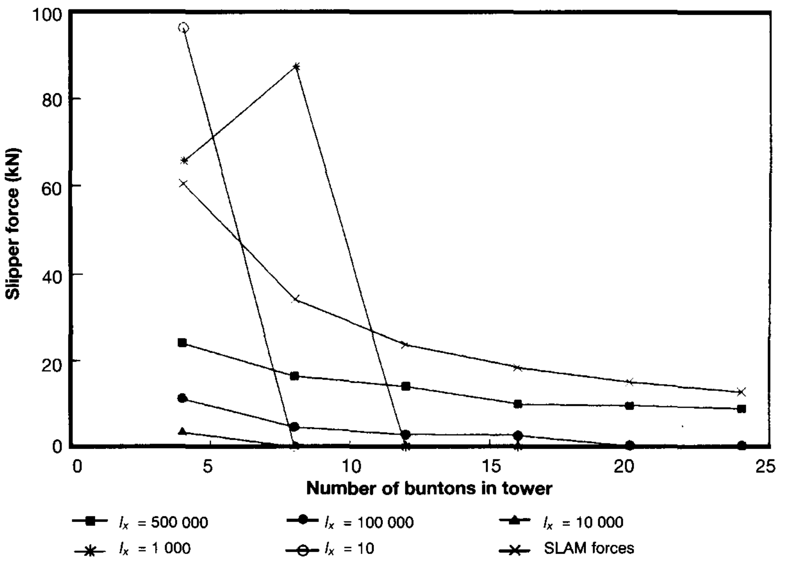

Figure 6—Maximum slipper forces predicted by DISCHANG

Table II

Slamming forces reduced by tower flexibility

No. of buntons	I_t (x 10^{-6} m^4)	F_s	
		e	kN
4	500 000	1974e	50,76
	100 000	1935e	49,76
	10 000	1742e	44,79
8	500 000	1935e	24,89
	100 000	1780e	22,89
	10 000	968e	12,45
16	500 000	1703e	10,95
	100 000	1045e	6,72
	10 000	232e	1,49

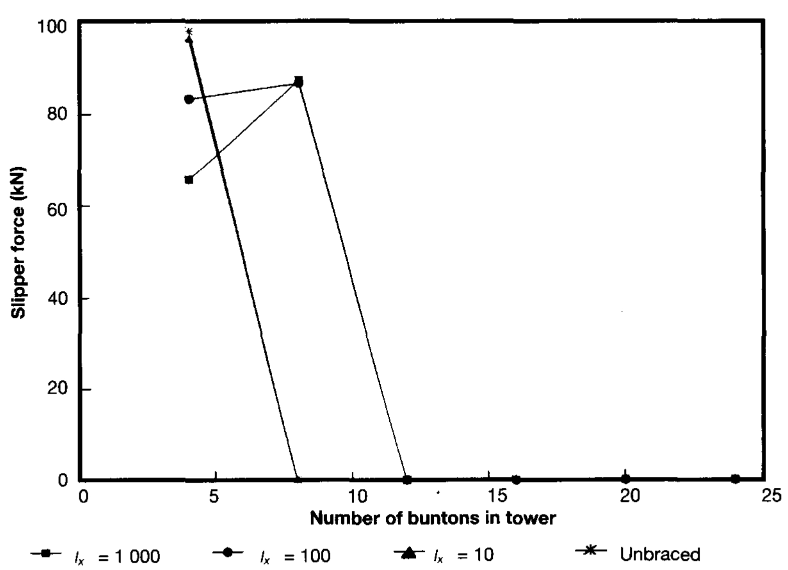

Figure 7—Slipper forces on unbraced tower and flexible braced tower

The behaviour of more flexible towers is somewhat more erratic. Very high forces result from the use of short towers, while the longer towers have zero force. The reason for this behaviour is that the lower flexibility allows greater displacement of the conveyance. In a short tower, the high slipper forces at the end of the tower result because there is insufficient time for the forces to centralize the conveyance before it encounters the stiff buntons beyond the tower. In a longer tower, the guides deform more than the roller springs, so no slipper contact develops. A longer tower nevertheless allows sufficient time for the conveyance to become centralized in the compartment before moving beyond the tower.

The behaviour of unbraced towers, as predicted by DISCHANG, is rather similar to that of flexible braced towers. Using the same parameters as listed in Table I, but with 16 guides, each having a second moment of area of 28 x 10^{-6} m^4, gives an equivalent tower I_x value of 448 x 10^{-6} m^4. The slipper forces predicted by DISCHANG are compared with those occurring in more flexible braced towers in Figure 7. This appears to be logical, as the only significant difference is in the S-shaped flow of a braced tower. The benefit of the slow transition from vertical guides to sloped guides is particularly important for stiff guides, and much less significant for flexible guides. It is thus assumed that the design of braced and unbraced towers can follow exactly the same procedure, providing that proper cognisance is taken of the appropriate stiffness values.

For a braced tower:

$$I_x = I_x.$$

For an unbraced tower:

$$I_x = (\text{Number of guides}) \times (\text{guide } I). \qquad [20]$$

Proposed design procedure

The results of the parametric study suggest a design procedure for braced shaft-steelwork towers that are suspended in isolation from the shaft walls. This design procedure may be formulated as follows.

Step 1. Check adequacy of the rollers.

The rollers are adequate if the ratio of the tower displacement frequency to the natural frequency of the conveyance is less than 0,4, i.e.

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$$r = \frac{\omega_t}{\omega_n} \le 0{,}4$$

$$\frac{\pi V}{L_t + L_c}\frac{3}{2}\sqrt{m_c\left(\frac{1}{2k_s} + \frac{L_t^3}{192EI_x}\right)} \le 0{,}4$$

$$\frac{V}{L_t + L_c}\sqrt{m_c\left(\frac{1}{k_s} + \frac{L_t^3}{96EI_x}\right)} \le 0{,}12. \qquad [21]$$

Step 2. Calculate slamming force.

The slamming force should be calculated using the method given by Thomas[8], with the stiffness modified as described in equation [19].

Conclusion

A numerical solution technique has been used to develop a computer program that models the behaviour of conveyances passing through a shaft tower that is isolated from the shaft walls to avoid the problems that would otherwise result from high strains in the surrounding rock. A simplified analytical procedure, and a parametric study using this program, have led to a proposed design procedure, that enables the design engineer to predict the maximum lateral forces, and the adequacy of any particular tower length and stiffness. ◆

Book Review

Minerals Handbook

Minerals Handbook 1994–95: Statistics and analyses of the world's minerals industry, by P. Crowsons, Basingstoke, Macmillan, 1994 ISBN 0 333 60931 X. £85. Available from Macmillan Direct Ltd., Houndmills, Basingstoke, Hants, RG21 2XS, UK.

Review prepared by Theo J. Oosthuizen, Information and Educational Programmes Division, Mintek

The seventh edition of the Minerals Handbook contains data for fifty commodity groups, including uranium, gold, chromium, manganese, and aluminium. The data has been updated to include annual figures for 1991–92. The handbook contains sufficient basic data on all aspects of the minerals and metals included to allow informed debate on mineral policies, and gives reasonably comprehensive introductions to each material covered.

The introductory summary tables are followed by separate sections on each of the commodity groups. These tables bring together data contained in the detailed sections, and summarize aspects of the mineral industries that influence public policy. The individual sections on each mineral follow a broadly common format, and include tables on reserves, mine production, refinery/smelter production, various production capacities, and consumption. End-use patterns, the value of annual production, substitutes, and technical possibilities are also dealt with, and average prices between 1988 and 1993 are also tabulated. The book is not intended as a substitute for other statistical publications, but is an excellent introductory guide for the non-specialist.

One major drawback of the handbook is that, the title of the book indicates that statistic are correct up to 1994–95, all the production figures are to the end of 1992, and those for prices to the end of 1993. ◆