G. Rebel
University of the Witwatersrand, Johannesburg, Republic of South Africa

The torsional behaviour of triangular strand ropes for drum winders

Summary

The torsional behaviour of Lang's lay triangular strand ropes will probably limit their application in very deep (2500 m - 4000 m) single lift shafts which the South African gold mining industry is planning for the future. These ropes have been used extensively on drum winding systems and it would be of technological and financial benefit if their application could be extended as far as possible. An improved understanding of the mechanisms which may lead to rope instability is however required. A research project was initiated in 1994 to investigate the torsional behaviour of wire ropes for drum winders, the results of which are summarised in this paper.

The first stage of the project was the development of a laboratory based wire rope torsion testing machine, capable of conducting tests at constant rope twist, load and torque. Lay length variations and the rotation behaviour of triangular strand ropes (41 - 54 mm) were subsequently measured in vertical shafts ranging in depth from 1000 m to 2500 m. Laboratory torsion tests were conducted to determine the torsional properties of the in-service ropes. Strength and ductility tests were also carried out on a 25 mm Lang's lay rope with different lay lengths to demonstrate the significance of lay length changes.

A new method of analysis has been developed which allows the calculation of in-service lay length variations and rope rotation during conveyance loading using the laboratory determined torsional properties. The rotation analysis takes into account changes in torsional stiffness resulting from the no-slip to slip transition associated with twist displacements. Predictions compare favourably with rope behaviour measured in existing shafts and the analysis is used to forecast the torsional behaviour in future shafts. Parameters which have the greatest influence on the torsional behaviour have been identified and recommendations are made on how the depth limit of application for triangular strand ropes may be extended.

1 Introduction

Lang's lay triangular strand ropes are used extensively for drum winding applications in South Africa. Mine shafts are typically fitted with fixed steel guides so non-spin rope properties are not required (Wainwright, 1990). In general, very good service lives are obtained from triangular strand ropes and the construction has proved to be particularly suited to the conditions of drum winding (resistance to crushing and good wear properties).

It is widely accepted that permanent torsional deformations occur in suspended triangular strand ropes as a result of rope load differentials and that the extent of the deformation increases with depth. It is also known that during winding operations the ropes show continuous torsional oscillations associated with variations in loading (Rebel et al., 1996a).

To date there has been no comprehensive method presented for calculating the torsional deformations (lay length changes) and rotation of ropes on drum winders. In general the understanding of rope torsional behaviour has tended to be qualitatively correct with little attention being given to detailed quantitative analyses. Although it is realised that significant torsional behaviour problems could be experienced at depths greater than 2500 m (current maximum) it is often assumed that the use of multi-layer non-spin ropes would provide a solution. However, Chaplin (1993) pointed out that the rather different fatigue properties of multi-strand ropes may lead to other problems in deep level applications. One of the main concerns is the predominant failure of internal rope wires and the ability to accurately detect these (Schrems, 1994; Kuun, 1993).

There exists substantial knowledge and experience in the manufacture and operation of triangular strand ropes in South Africa. The use of these ropes to the maximum possible depths will therefore be of considerable benefit to the industry. The present study was initiated in anticipation that the torsional behaviour will be the main limiting factor. By improving the understanding of rope behaviour and identifying the parameters which have the greatest effect on torsional deformation, it is probable that the limit of application could be extended. It is also considered likely that the investigation would provide information with which the performance of ropes in existing installations could be improved.

2 Objectives and scope of the project

The primary objective of the project was to determine and verify a model which could predict the static torsional behaviour of Lang's lay triangular strand ropes operating on vertical shaft drum winders. The calculated parameters of interest were :

- lay length changes at rope installation taking into account manufacturing details, installation geometry and applied loads;
- variations in lay length with service period as a result of maintenance practices;
- rotation of vertically suspended ropes during conveyance loading;
- rope torques for empty and loaded conveyances.

The first stage of the project involved the development of a laboratory based rope tension-torsion testing machine which has be described previously (Rebel and Chandler, 1996). The main requirement was that the machine should perform torsion tests at constant rope load, twist and torque by means of computer control. In its previous form, the machine was capable of measuring rope torque for manually set constant end rotations (twists) and varying values of load. It was anticipated that the results of tests conducted at constant load and torque would indicate rope characteristics different from those explored by the constant twist method.

The development of the testing machine was followed by a series of in-service measurements. Lay length and rope rotation data of 22 ropes were collected from eleven shafts. The rope diameters varied from 41 mm to 54 mm and the shaft depths were in the range 1000 m to 2500 m. Men-material and rock winders were considered.

Laboratory torsion tests were conducted on samples matching the construction and diameter of the in-service ropes. The experimentally determined torsional properties, combined with the necessary analysis and assumptions, were used to calculate the in-service behaviour. Predictions from the modelling were then verified by comparison with in-shaft data.

3 Experimental approach

3.1 In-service measurements

Lay length measurements were conducted on surface with the conveyance moving up the shaft. It was assumed that, for a given state of loading, the rope does not rotate when the conveyance is hoisted upwards. Site observations confirmed this assumption which was based on rope rotation theory discussed by Hankus (1993).

Rotations of the ropes, during conveyance loading, were recorded at different positions along the suspended lengths. The procedure involved moving to different levels in the shaft and video filming paint marks on a rope while the conveyance was being loaded. This method was preferred to the traditional "chalk line" approach, described by Yiassoumis (1992), as it resulted in the minimum disruption to the normal shaft operation. The paint marks were positioned 90° apart resulting in a rotation resolution of approximately 45°.

3.2 Laboratory torsion tests

Investigation of the torsional properties of triangular strand ropes concentrated on the constant twist and load type tests. The constant twist tests were of a very similar nature to those previously reported by Feyrer and Schiffner (1987). Particular attention was given to ensuring that the applied twists produced relatively large changes in lay length, comparable to those which would be expected in a deep shaft hoisting installation. Figure 1 shows the results for a 46 mm triangular strand rope. The variation in lay length and the applied twists are indicated on the right of the curves.

Raoof and Hobbs (1989) demonstrated that inter-wire friction in multi-layered structural strands can have a significant effect on their response to applied torques. It was shown that a spiral strand exhibits a nonlinear relationship between applied torque and twist and that the torsional stiffness of the strand is a function of the twist displacement and the mean load. The behaviour was ascribed to a transition from a state of *no-slip* between the wires, for small perturbations, to *full slippage* at larger twist deformations. Raoof and Hobbs suggested that as the mean axial load is increased, the onset of full slip is delayed as a result of increased inter-wire contact forces.

Even though triangular strand ropes have considerably different geometric properties to spiral strands, it was expected that on a qualitative basis they would exhibit similar behaviour. Further investigation revealed that the torsional stiffness of these ropes is a function of the twist displacement from a stationary position, the direction of twisting, the load at which twisting occurs and the starting value of twist. In order to fully quantify the torsional stiffness characteristics it was necessary to conduct torsion tests for different constant loads and starting twist values, as shown in Figure 2. The changes in lay length corresponding to the twist starting values and the constant loads are indicated. The results in Figure 2 are the averages of the twisting up and untwisting responses. For all loads and starting values of twist, triangular strand ropes have a higher stiffness in the twisting up direction than for untwisting. This phenomena was first demonstrated by Layland et al. (1951) who found that in the case of a torsion pendulum (6 strand Lang's lay rope) damping appeared to be greater in the laying up direction of rotation than in the unlaying direction. The torsional stiffness determined from the data in Figure 2 is shown in Figure 3.

4 Effects of lay length on rope strength and ductility

Wainwright (1988), McKenzie (1990) and Greenway (1990) have all reported that excessive lay length changes are expected on drum winding systems with large suspended rope lengths. Values of 30 to 40 percent shortening at the conveyance end and 50 to 80 percent increases in lay length from nominal at the drum end were referred to. Traditionally much emphasis has been placed on the results of destructive tests in assessing the condition of hoisting ropes but the in-service variations in lay length have not been taken into account. In this regard, Kuun et al. (1993) questioned whether the strength of a short sample removed from a discarded rope is truly representative of that section of rope under operating conditions. It was further stated that due to factors, of which shaft depth and maintenance practices are most important, the lay length of a free sample of rope can vary considerably from its in-service lay length. The effect of this variation on the strength of a discarded rope was not known.

To answer some of these questions, 28 tensile tests on a 25 mm compound triangular strand rope with different lay lengths were conducted. The rope samples were all cut from the same new rope coil. The lay lengths were changed manually prior to testing using a torque clamp attached to one of the white metal collars (two 800 mm moment arms). Both end cones were locked in the grips by placing a preload on the rope. The torque clamp end was then loosened prior to inducing or removing rotations, while the other end remained fixed.

Figure 4 shows the measured change in breaking strength for a variation in lay length. Three reference tests were conducted at the free lay length and their average was used to calculate the % variations.

As was the case with twelve preliminary tests of this type (Rebel, 1995) there is a sharp decrease in breaking strength with a decrease in lay length. The strength increases marginally with an increase in lay length and thereafter tends to decrease. This is expected since there is a limit to which the construction can be upset before the benefits of reduced spinning losses are outweighed by the additional wire stresses imposed. Three of the tests results are marked :

- MD - Mechanical Damage, three outer wires in one strand showed transverse abrasion marks along 6 mm of the wire axes.
- ECPO - Strands failed inside the white metal cone, End Cap Pull Out.
- ECF - Strands failed at the white metal collar, End Cap Failure.

For the data in Figure 4, a decrease in nominal lay length of thirty percent corresponds to a decrease in breaking strength of approximately ten percent (from nominal). This result justifies the South African specification that a thirty percent decrease in lay length from nominal is reason for discard of a hoisting rope (Kuun et al., 1993).

Materials which undergo large strains before failure are generally classified as ductile. An indication of ductility can be determined by dividing the elongation at failure by the gauge length (measured after the lay length change), Figure 5. The elongation measurement includes elastic deformation of the testing machine as well as settling in of the cones into the grips. Since all the specimens were prepared in the same manner it is assumed that the results are subject to the same errors and can be compared with reasonable accuracy. The specimen with mechanical damage showed a sharp decrease in strain at failure.

5 In-service lay length and rotation analysis

5.1 General equations for describing rope torsional response

To calculate the in-service lay length changes and rope rotation, it is necessary to define an equation which relates rope torque to the applied load and twist. For this purpose, Hermes and Bruens (1957) presented equation (1) :

$$M = C.F + T.\frac{d\phi}{dz} \qquad (1)$$

where : M = rope torque (Nm)

$d\phi/dz$ = rope twist relative to an initial lay length (°/m)

F = rope load (kN)

C = constant of proportionality between load and torque (Nm/kN)

T = torsional stiffness constant (Nm/(°/m))

Glushko (1966) later proposed a two degree of freedom elastic system, equation (2), which has been applied more recently by Hankus (1993,1995).

$$A_1.\frac{du}{dz} + C_1.\frac{d\phi}{dz} = F(z)$$

$$(2)$$

$$C_1.\frac{du}{dz} + B_1.\frac{d\phi}{dz} = M(z)$$

where A_1, B_1 and C_1 are constants for a particular rope construction.

Considering only rope twist, $d\phi/dz$, in equation (2) yields an equation of the same form as (1) where :

$$C = \frac{C_1}{A_1} \quad \text{and} \quad T = \frac{A_1 \cdot B_1 - C_1^2}{A_1} \qquad (3)$$

Kollros (1976) developed a revised equation for torque which included a product between load and twist. Feyrer and Schiffner (1986) made slight modifications to the equation of Kollros, describing rope torque by equation [4].

$$M = C_1.F + C_2.F.\frac{d\phi}{dz} + C_3.\frac{d\phi}{dz} \qquad (4)$$

In all cases it was suggested that the values of the constants in the torque equations could be determined analytically or by experiment. From the outset of this project it was decided that the determination of rope properties through laboratory testing would be most prudent (need to cater for non-circular strands and the effects of friction). It was however found that equation (4) could not adequately describe the typical triangular strand rope test data shown earlier in Figure 1. A more detailed equation was therefore adopted to allow for non-linear relationships between load, torque and twist which become evident at larger deformations :

$$M = \begin{bmatrix} R^2 & R & 1 \end{bmatrix} \cdot \left[\begin{bmatrix} N_{11} & N_{12} & N_{13} \\ N_{21} & N_{22} & N_{23} \\ N_{31} & N_{32} & N_{33} \end{bmatrix} \cdot \begin{bmatrix} F^2 \\ F \\ 1 \end{bmatrix} \right] \qquad (5)$$

where R = rope twist, $d\phi/dz$ (°/m)

Using established numerical techniques, the entries (constants) in the matrix **N** are solved for from the torsion test data in digital form (constant twist test). For the loading values of torque in Figure 1 :

$$\mathbf{N} = \begin{bmatrix} 1.5829e-009 & 4.2655e-007 & 1.1605e-003 \\ -1.0236e-006 & 5.8743e-003 & 1.5374e+000 \\ 8.4110e-005 & 5.0628e+000 & -1.0342e+001 \end{bmatrix} \qquad (6)$$

The linear variation in rope load along a suspended length is described by equation (7):

$$F(z) = P + q.z \qquad (7)$$

where : P = rope end load (kN);

q = rope weight per unit length (kN/m);

z = distance along the rope, from the conveyance end (m).

Substituting (7) into (5) and rearranging into a quadratic in terms of twist (with the positive root as solution) results in a general equation for rope twist along the suspended length :

$$R = f(M,P,q,z) \tag{8}$$

The rotation along the rope can be determine by integration:

$$\phi = \int R(M,P,q,z)\,dz + constant \tag{9}$$

5.2 Calculation of installation equilibrium conditions

Gibson (1980) explained that the torque, M, in a suspended rope must be constant along the length of the rope if there are no externally applied torsional loads. The value of constant torque is however unknown and needs to be solved for using the in-service boundary conditions. Boundary conditions in terms of twist, R, cannot be defined but the rotation boundary conditions, $\phi(0)$ and $\phi(L)$, can be determined. The positions, $z = 0$ and $z = L$ refer to the splice and sheave ends respectively. It has been common practice in the past to assume that the rotation at the conveyance (splice) and drum (sheave) ends of the rope are both zero at installation. This implies that all portions of the rope must be in a state of zero twist prior to being suspended in the shaft. Twist is a relative quantity which is dependant on the lay length of the torsion test specimen at installation in the testing machine. Inevitably, the lay length of a short, free section of rope will be longer than the lay length of a newly manufactured rope coiled directly onto a take-up reel. The analysis must therefore take into account the lay length at which a rope was manufactured in determining the boundary conditions.

The twist, R_{coil}, corresponding to the manufactured lay length (LL_m) is determined from the torsion test data (Figure 1). With reference to Figure 6, if the total length of rope installed on the winder is z_{max} and the rotation at conveyance end is assumed to be zero, then the rotation at the drum connection point must be $R_{coil}.z_{max}$. That is if no rotation was lost from the rope during installation. The initial twist and rotation distribution in the suspended section can then be calculated using equations [8] and [9] knowing the boundary conditions :

$$\phi = 0 \quad \text{at} \quad z = 0$$

$$\phi = R_{coil}.L \quad \text{at} \quad z = L$$

Two boundary conditions are required to solve for the constant of integration in equation (9) and the unknown constant torque, M.

If only the suspended section is considered ("Initial rotation") then it is apparent that the lay length between the sheave and the drum connection point remains unchanged ($LL = f(d\phi/dz)$). In practice a rope is continuously wound on and off the drum so the lay length of the rope permanently coiled on the drum would be affected in time by the altered rotation distribution in the suspended section (Gibson, 1980). As an approximation, it can be assumed that an equilibrium state is reached when the lay length between the sheave wheel and the drum connection point equals the lay length in the suspended section adjacent to the sheave (i.e. *Slope 1 = Slope 2*).

In attaining the equilibrium state, the rotation boundary condition at the sheave will change but the drum connection point rotation value will remain constant (i.e. pivot point). The numerical scheme adjusts the sheave wheel boundary condition (*SWbc*) and then calculates the new twist and rotation distributions in the suspended section as well as the constant twist (*Slope 2*) between the sheave and the drum connection point. The process is continued until the equilibrium value of *SWbc* is determined. After the installation equilibrium conditions have been calculated, rotation lost from the rope due to maintenance operations can be modelled by increasing the boundary condition at the conveyance end (ϕ_{lost}).

5.3 Calculation of rope rotation during conveyance loading

When a conveyance is loaded there is an equal increase in load at every point along the suspended rope length (ignoring dynamic effects). If the general relationship between load, torque and twist is considered (equation (5))then it is apparent that the increase in load must be accompanied by an increase in torque, as indicated in Figure 7. If the increase in load occurs at constant twist, then the resulting torque in the rope ($M_{f,Re}$) will vary along the length.

The loading process can be divided into two parts :

1. An increase in load at constant twist, R_e.
2. A change in twist at constant load to establish a new torque equilibrium, M_f.

The rope achieves the change in twist by rotating. The magnitude of twist is dependant on the torsional stiffness of the rope and the required change in torque. Since the twisting takes place from a stationary position, the relationship between twist and torque would be of the general hysteretic form shown earlier in Figure 2.

Using the rope load distribution, $P_f + q.z$, the empty conveyance twist distribution, $R_e = d\phi_e/dz$, and the data shown in Figure 2 it is possible to determine the relationship between twist and torque at all positions along the suspended rope (linear interpolation).

The required change in torque is determined by subtracting the torque calculated for an increase in load at constant twist, $M_{f,Re}$ from the equilibrium torque, M_f. Knowing the change in torque (ΔM) required at each position along the rope and the relationship between torque and twist, the change in twist (ΔR) can be determined. Integrating the change in twist gives the change in rotation ($\Delta\phi$) along the rope which is easily compared to the site observations.

The process of solving for the loaded conveyance equilibrium condition is iterative since the torque, M_f, has to be chosen such that the change in rotation values at the splice and sheave are zero. The splice end of the rope untwists and the sheave end twist up in order to establish a torque equilibrium for the loaded conveyance. It follows that the rope rotation during loading is in the opposite direction to the original rotation for the empty conveyance equilibrium condition (i.e. $\phi_f < \phi_e$).

6 Comparison between calculated and measured results

6.1 Example of a 46 mm rope at 2403 m suspended length

For illustration, the calculated and measured data for the deepest shaft considered will be compared. The main parameters of the winding system for this shaft were :

P_e	=	70.0 kN	(man cage and attachments)
P_f	=	137.7 kN	(Diesel locomotive as payload)
q	=	0.0895 kN/m	
L	=	2403 m	
z_{max}	=	2824 m	
R_{coil}	=	90 °/m	(355 mm, from data in Figure 1)
ϕ_{lost}	=	1406.7 turns	(calculated knowing measured lay lengths)
$SWbc$	=	802.4 turns	(calculated for installation equilibrium)
Rope	:	46 mm, 6x31(13/12/6+3Δ)/F, 2150 MPa, RHL	

Figure 8a shows the change in twist for three different payloads (67.7 kN ± 15%). Numerical integration of the calculated twist during loading gives the rope rotation which is compared to the measured rotation values in Figure 8b. Figure 8c shows the rotation distributions for the rope as it was received by the mine (ϕ_{coil}) and after installation for an empty conveyance (ϕ_{ei}). The empty (ϕ_e) and loaded (ϕ_f) rotation distributions at the time of the measurements are also shown. The difference between ϕ_e and ϕ_f corresponds to the solid line in Figure 8b. For each rotation distribution, the associated twists and lay lengths can be calculated. Figure 8d compares the calculated lay lengths to the lay lengths which were measured after installation and at the time of the measurements.

The actual amount of rotation lost from the rope during maintenance operations is not known since rope maintenance staff do not take note of the turns lost. In Figure 8d, the change in lay length from installation (LL_{ei}) to the time of measurements (LL_e) is a direct result of deliberate unlaying of the rope. It was mentioned earlier that unlaying of the rope can be simulated by increasing the rotation boundary condition at the splice. It can therefore only be shown that, at some point of unlaying, the calculated lay length values correspond to the measured values. In doing this, the only variable in the analysis algorithm that is altered is ϕ_{lost}.

The specific relationship between change in torque and change in twist used for calculating the rope rotation during loading is shown in Figure 9. The corresponding torsional stiffness characteristic along the rope is plotted in Figure 10. The variation in the torsional stiffness along the rope is considerable. At the splice end ($z = 0$) the no-slip torsional stiffness is almost seven times greater than the full-slip stiffness. The values shown in Figures 9 and 10 are again the averages of the twisting up and untwisting responses measured during the torsion tests (constant load, Figure 2). It was found that using the average stiffness values resulted in acceptably accurate results for all the ropes. In practice, loading of a conveyance is a dynamic event in which the rope exhibits torsional oscillations. The final static change in rotation is therefore dependant on the twisting up and untwisting stiffnesses.

Using the equation for torque, (4), Hecker and van Zyl (1993) and Rebel et al. (1996a) presented rope rotation calculations in which the rotation distribution for the loaded conveyance was determined by the same method as for the empty conveyance (i.e. P_e replaced with P_f). The approach neglects hysteresis effects in the torsional response, resulting in considerable errors. For the example shown in Figure 8b, the maximum rotation during loading, $\Delta\phi_{max}$, was calculated to be 46.7 turns (as opposed to 13.0) using only the torsional relationships described by equation (5).

6.2 Accuracy of analysis method

Figures 11 and 12 show the error values calculated from the lay length and rotation predictions for the 22 ropes considered in the project. The errors were determined by subtracting the measured values from the calculated values, as in Figures 8b and 8d. In the case of the lay lengths, 86.1 percent of the errors lie in the range plus and minus two percent of the nominal rope lay lengths. For the rotation errors, 80.5 percent are in the range plus and minus one turn. The rope rotation at the splice and sheave ends during loading are known to be zero and were not taken into account in the calculations for Figure 12.

7 Factors influencing the in-service torsional behaviour

The level of correlation between the measured and calculated results shows that the analysis method is capable of producing acceptably accurate predictions of the static torsional behaviour. Large variability in the parameters between the eleven shaft installations did not allow for conclusions to be drawn directly from the raw data. Using the verified modelling approach, factors such as rope diameter, manufactured lay length, deliberate loss in rotation and rope weight per unit length were identified as being important as regards the torsional behaviour of triangular strand ropes.

7.1 Selection of shaft parameters for investigation

The maximum suspended lengths were taken as 500, 1000, 1500, 2000, 2500, 3000 and 3500 m. Laubscher (1995) presented a new equation,(10), for calculating rope selection factors (*RSF*). For the calculations, conveyance weights and payloads were based on the load carrying capacity determined using equation(10).

$$RSF = \frac{25000}{4000 + L} = \frac{EBL}{F_{max}} \qquad (10)$$

where :

L = maximum suspended length (m);

L = estimated rope breaking load (kN);

F_{max} = maximum static load applied to the rope, including rope weight (kN).

The ratio of conveyance weight to payload was set at 0.68 which is a realistic value for rock hoisting. It was initially assumed that the ropes were all manufactured at their nominal lay lengths (LL_{nom}) plus 3.71 percent (average for 122 ropes). The distance between the sheave and the drum connection point ($z_{max} - L$) was taken as 370 m (average for 32 winding installations). For q and EBL the catalogue values were used (Haggie Rand, 1987).

7.2 Influence of rope diameter

Figure 13 shows how the calculated rope lay lengths vary at installation for seven diameters. The ropes of smaller diameter are subject to smaller variations in the splice and sheave end lay lengths. Figure 14 shows the maximum rope rotation values calculated for the diameters from 41 mm to 54 mm. The curves are truncated where the load or twist values exceeded the ranges for which stiffness data was available. The trend is for the rotation to increase with an increase in diameter except in the case of the 54 mm rope. For all the diameters shown in Figure 14, the maximum rotation increases with the square of depth up to 2000 m. Between 2000 m and 3500 m the further increase in rotation is approximately linear.

Figure 15 shows the variation of the equilibrium rope torque for an empty conveyance for seven rope diameters and changing depth. For a given diameter, the increase in torque is approximately linearly related to the maximum suspended length. At a given suspended length, the torque increases with diameter to the power of 3.28 ($M_{ei} \approx constant.d_{nom}^{3.28}$). It was found that the average ratio of loaded torque to empty torque (M_{fi} / M_{ei}) equalled 1.98 at 500 m; 1.60 at 2000 m and 1.38 at 3500 m.

7.3 Effect of manufactured lay length and rotation losses

Lang's lay triangular strand ropes can be manufactured with different lay lengths. The manufactured lay length (LL_m) has a fairly significant effect on the lay length changes at installation, Figure 16. Other than manufacturing anomalies, the most probable cause of an increases in the lay length is the loss of rotation from the rope during installation. If rotation is lost from a rope, it has the same effect as if the rope was manufactured with a longer lay length. A longer rope will however be less affected by a given loss in rotation than a shorter rope. Figure 16 shows that the sheave end lay length is affected considerably more than the splice end by changes in LL_m.

Figure 17 shows how the rope rotation during conveyance loading increases with an increase in the manufactured lay length. At 3000 m, a 15 percent increase in the lay length (from 5 percent to 20 percent) results in a 43 percent increase in rope rotation.

7.4 Effect of varying rope weight per unit length

The primary cause of lay length variations and rotation of Lang's lay ropes used on drum winders is the load differential along the rope which is dependant on the rope weight per unit length, q. It was shown in Figure 13 that smaller diameter ropes are less prone to lay length changes than those of larger diameter. If smaller diameter ropes of reduced weight per unit length (compared to current designs) were to be used in very deep shafts, there could be considerable benefits in terms of lay length changes.

Calculations were conducted on the 41 mm rope at a ten and twenty percent reduction in rope weight, with the *EBL* remaining constant, Figure 18. The standard 41 mm rope would have the same splice end lay length at 3500 m that the larger ropes (48 mm and 49 mm) have at 2650 m. The sheave end lay length of the standard 41 mm rope at 3500 m would occur at approximately 2940 m with the larger ropes. If the weight of the 41 mm rope is reduced by ten percent, without changing the torsional properties or the breaking strength, then the splice and sheave end lay lengths at 3500 m occur at 2330 m and 2640 m respectively for the larger ropes. If the weight per unit length could be reduced by twenty percent then the values would be to 2000 m and 2340 m. Replacing wires in the rope construction with high strength, light weight materials (eg. Aramid) would probably tend to reduce the torsional response resulting in added benefit.

The reduction in rope weight per unit length at constant breaking load implies that the attached mass and payload should increase. The reduction in rope rotation due to the reduction in rope weight is opposed by the increase in payload. Therefore, the rotation during conveyance loading (Figure 14 : 41 mm) varies only marginally for the differing rope weights per unit length.

8 The limit of application, possible solutions and recommendations

Lay length data for more than 120 ropes were examined and it was found that in very few cases the splice end was shorter than 20 percent decrease from nominal and none of the lay lengths exceeded a 70 percent increase at the sheave end. Very short lay lengths at the splice end (< -20%) would make that portion of the rope extremely prone to distortion in the form of kinks and corkscrews. These distortions are mostly reason for immediate discard.

It is proposed that the splice end lay length should not be operated at more than 20 percent shortening from nominal. It is now possible to calculate the lay length at which a rope should be manufactured so that upon installation the splice end lay length has the desired value. For example, in the case of the 46 mm rope data shown in Figure 16, if the rope was manufactured at the nominal lay length plus ten percent then at 3000 m the lay lengths at installation would be approximately correct. No rotation would have to be released from the rope after installation and the lay lengths could be more or less maintained for the entire service life.

Considerable increases in lay length may affect the endurance. Although this has not been quantified, Rebel et al. (1996b) cited numerous references which suggest that unlaying of Lang's lay ropes has a negative influence on endurance. Further references to support this view included Haller (1989) and Oplatka (1994). Investigations should be conducted to determine whether the effects of lay length on endurance are significant under tension-tension and bending fatigue (*D/d* ratios from 80 to 120). If the effects are significant then rope life could be improved on existing installations by altering the rope maintenance practices.

It was shown in Figure 17 that rope rotation during conveyance loading increases significantly with increases in lay length, particularly at depth. The implications of increased cyclic torsional activity on rope endurance have to be considered especially in the case of rock winders where the conveyance may be loaded between 300 and 600 times per day. If the increased cyclic rotation is regarded as detrimental then there is further argument against allowing deliberate unlaying. For the example shown in Figure 8, the calculated rotation at installation was 6.59 turns (i.e. ϕ_{ei} - ϕ_{fi}). The unlaying ($LL_{ei} \rightarrow LL_e$) therefore resulted in a doubling of the maximum rope rotation for the particular payload (67.7 kN).

If the current practice of allowing ropes to unlay in service is adopted for very deep shafts then 3000 m suspended length may not even be possible. By altering the lay lengths at which ropes are closed and modifying the maintenance practices, 3500 m could well be achieved. Reductions in rope weight per unit length of the order of 20 percent could make suspended lengths of greater than 3500 m viable. This forecast does not take into account the amplitude of torsional oscillations associated with dynamic events. In a preliminary investigation, Rebel (1997) showed that during emergency braking the maximum dynamic torsional amplitude increased from 2 turns at 760 m to 26 turns at 2000 m on nominally similar winding systems. These observations should be of concern to rope manufacturers and users and further investigations are recommended.

9 Conclusions

Experiments have shown that lay length changes can result in significant variations in the measured mechanical properties of triangular strand ropes. It is recommended that further research relating to condition assessment of these ropes should take into account in-service lay length changes. It should also be considered that the sensitivity of the rope construction to damage (corrosion, abrasion, plastic deformation or broken wires) may be a function of lay length.

A verified modelling approach has been developed which allows accurate calculation of in-service lay length changes and rope rotation of triangular strand ropes operating on drum winders. It has been found that torsional hysteresis constitutes a first order effect in the calculation of rope rotation during conveyance loading. It was also noted that in-service rotation boundary conditions can be significantly affected by the difference between the lay length at which a rope is manufactured (closed) and the zero twist lay length for laboratory torsion tests.

Predictions of lay length changes and rope rotation have been presented for suspended lengths up to 3500 m. Severe shortening of the splice end lay length can be expected at depths greater than 2500 m but this can be alleviated by increasing the lay length at which the ropes are manufactured. The most significant changes in sheave end lay lengths are caused by deliberate unlaying of the rope. It is proposed that this action has a negative effect on rope endurance and further site and laboratory investigations are required.

The reduction of rope weight per unit length, changes in rope maintenance practices and the use of more ropes of smaller diameter could see the Lang's lay triangular strand design being applied at suspended lengths in excess of 3500 m.

10 Acknowledgements

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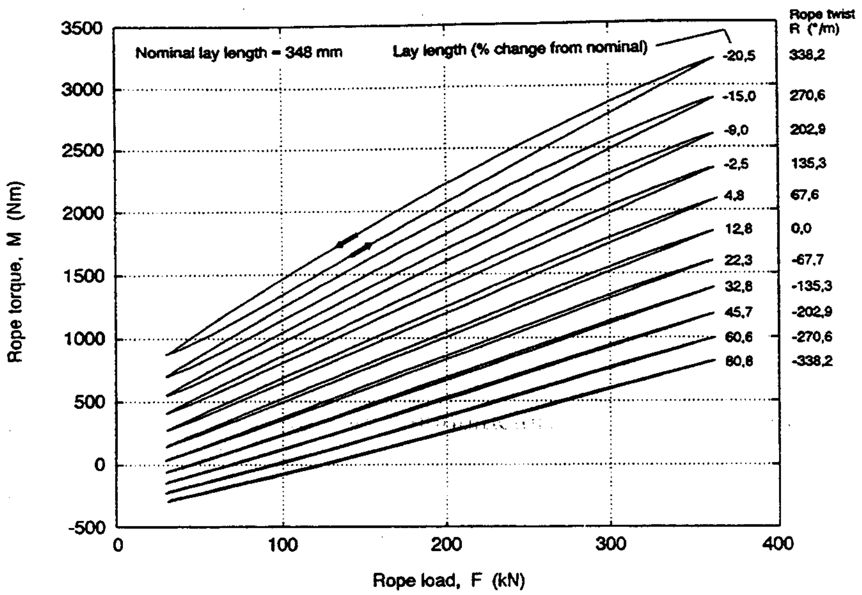

Figure 1: Typical torque versus load results for a constant twist test. Loading and unloading data are shown for a 46 mm triangular strand rope, 6x31(13/12/6+3Δ)/F, RHL, 1800 MPa, zero twist gauge length = 2661 mm. Convention : RHL ropes generate positive torques and positive twist shortens lay length.

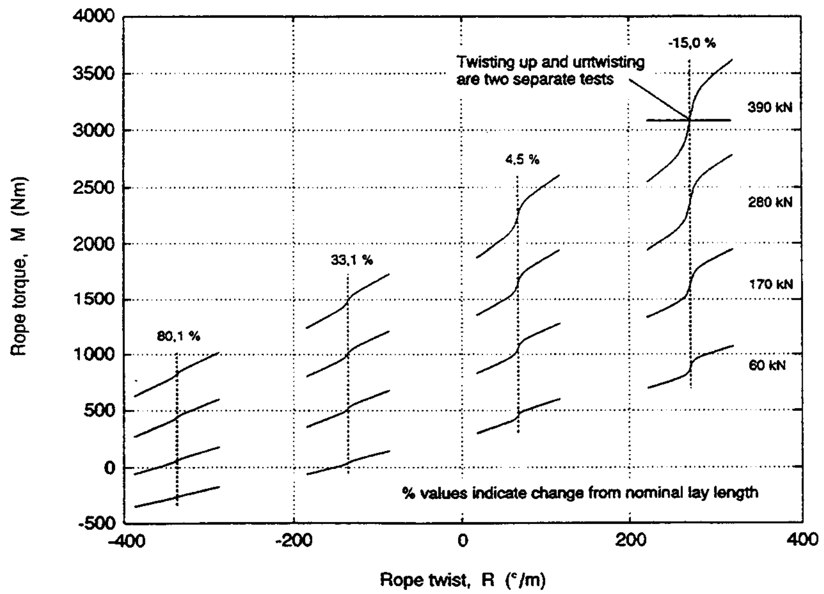

Figure 2: A series of constant load tests to determine the detailed hysteretic relationship between torque and twist, 46 mm triangular strand rope, 6x31(13/12/6+3D)/F, RHL, 1800 MPa, zero twist gauge length = 2661 mm. Curves shown represent the averages of the twisting up and untwisting responses.

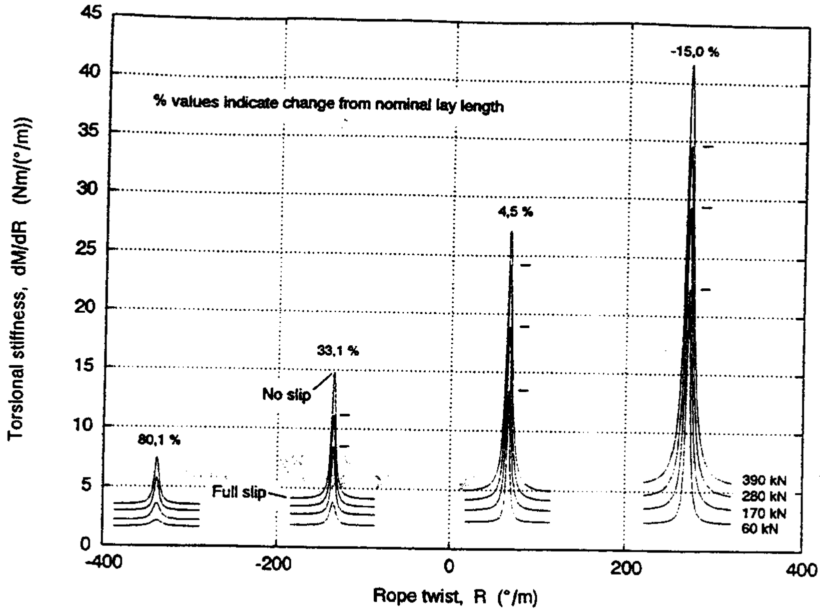

Figure 3: Variations in torsional stiffness for the constant load tests shown in Figure 2. Note that for given starting twist value, the full slip stiffness is dependant on the axial load.

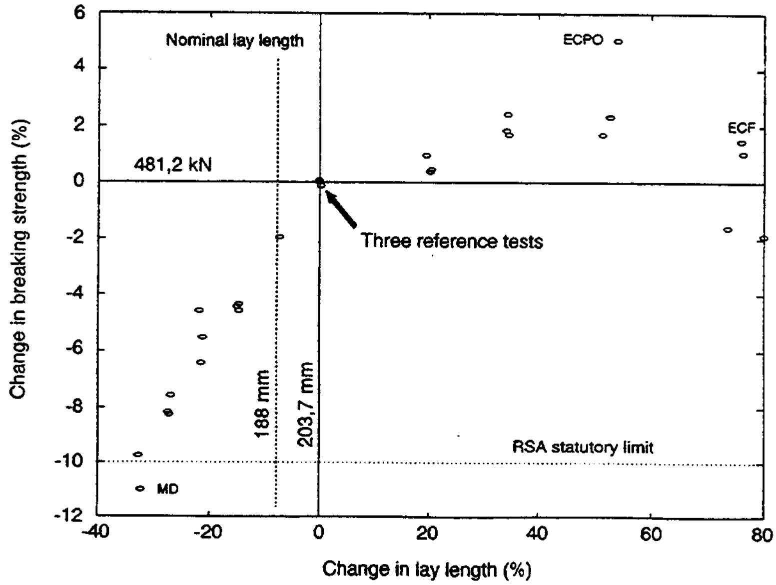

Figure 4: The effect of changes in lay length on breaking strength for a 25 mm Lang's lay triangular strand rope:The effect of changes in lay length on breaking strength for a 25 mm Lang's lay triangular strand rope, 6x27(9/12/6+3Δ)/F, 1800 MPa, RHL, average gauge length prior to twisting = 2500 mm.

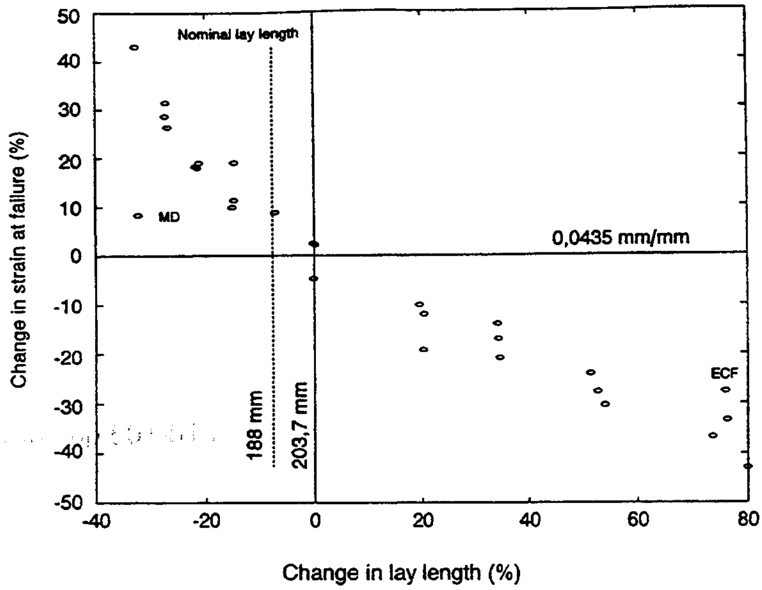

Figure 5: Total strain at failure for :Total strain at failure for changes in lay length of a 25 mm Lang's lay triangular strand rope, 6x27(9/12/6+3Δ)/F, 1800 MPa, RHL.

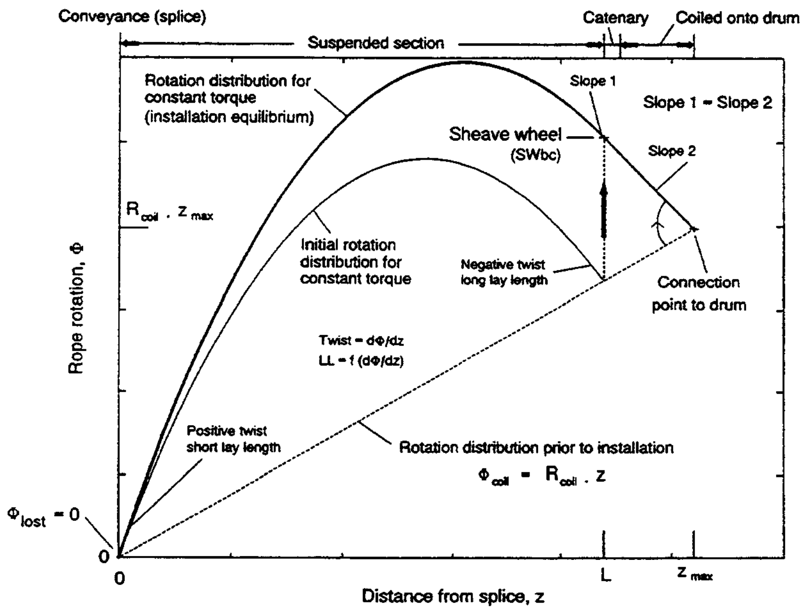

Figure 6: General form of the equilibrium rotation distribution after installation. Torsional interaction between the vertical and drum side sections of rope is taken into account in calculating the installation equilibrium distribution.

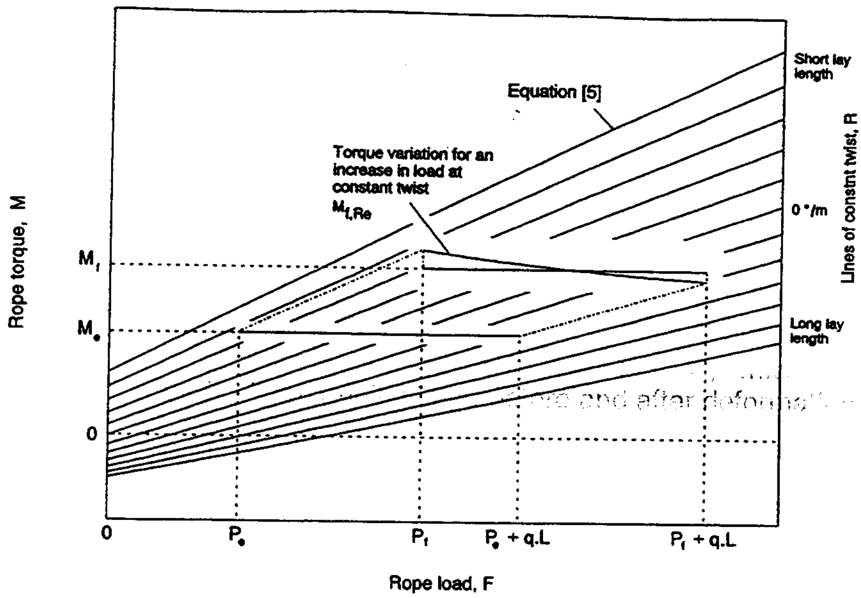

Figure 7: Changes in rope torque as a result of conveyance loading.

P_e	=	empty conveyance rope end load (kN)
P_f	=	loaded conveyance rope end load (kN)
M_e	=	equilibrium rope torque for the empty conveyance (Nm)
M_f	=	equilibrium rope torque for the loaded conveyance (Nm)
R_e	=	twist distribution for the empty conveyance (°/m)

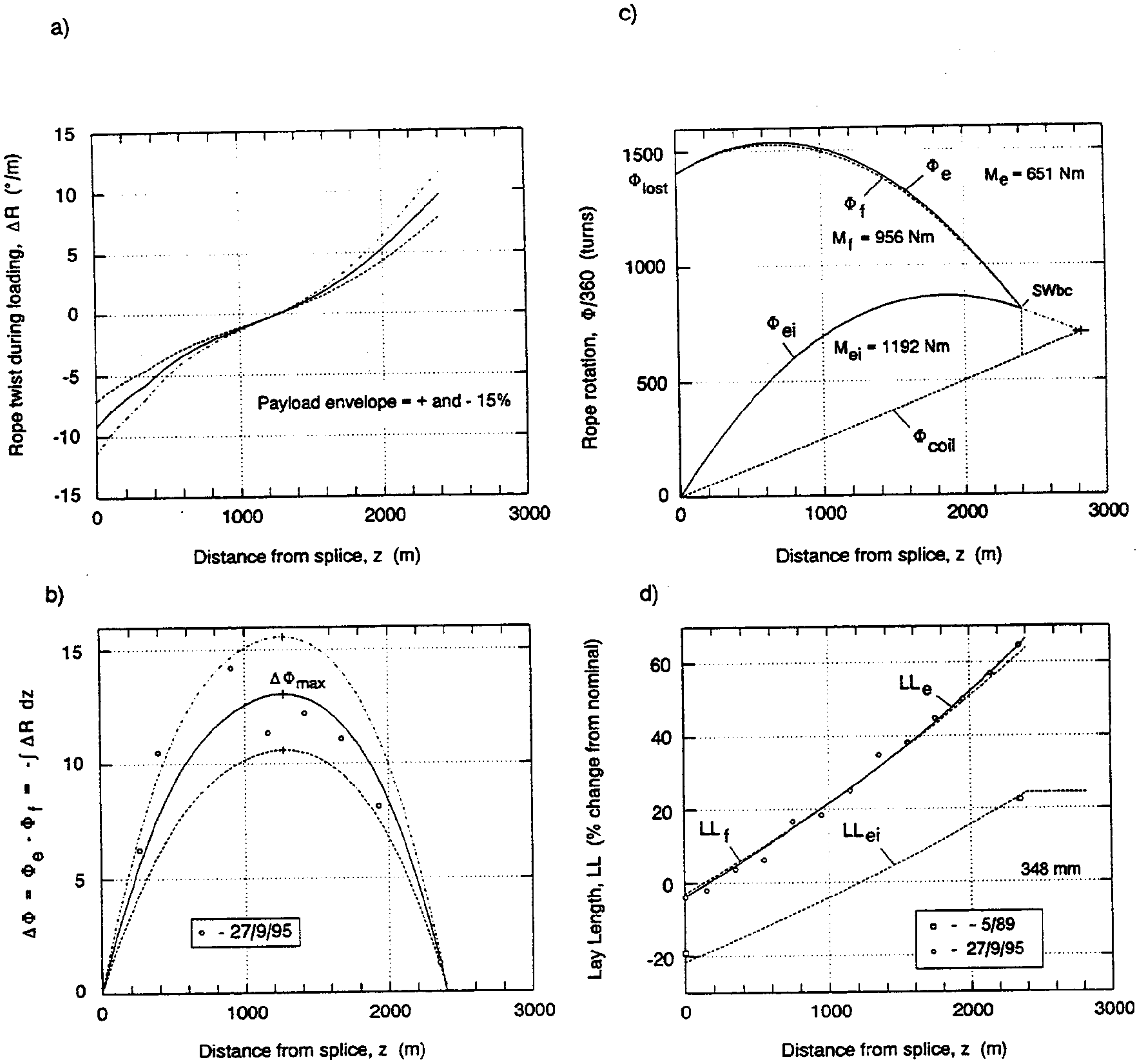

Figure 8: Example of the calculated and measured results for a 46 mm triangular strand rope operating with a suspended length of 2403 m. Note the scatter in the measured values of $\Delta\Phi$ in spite of the fact that a locomotive of fixed weight was used for loading of the conveyance. The variation in torsional stiffness along the rope, used in the calculations for a) and b), is shown in Figure 10. The subscript "*ei*" refers to the empty conveyance at installation.

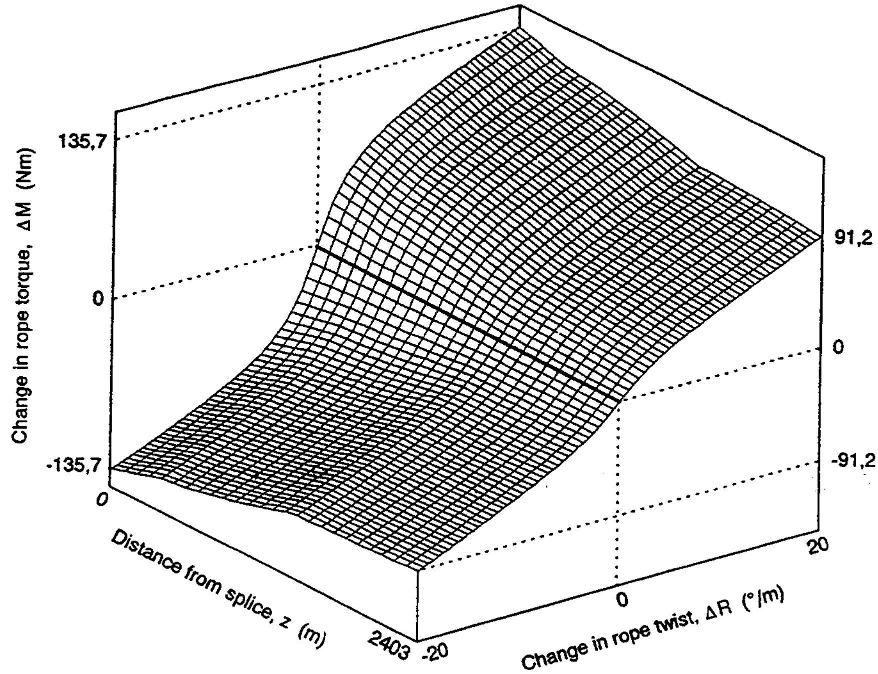

Figure 9: Torsional response due to changes in twist along the suspended rope, determined from the data lin Figure 2 using the twist distribution, $R_e = d\phi_e/dz$ (Figure 8c) and the load values $P_f + q.z$.

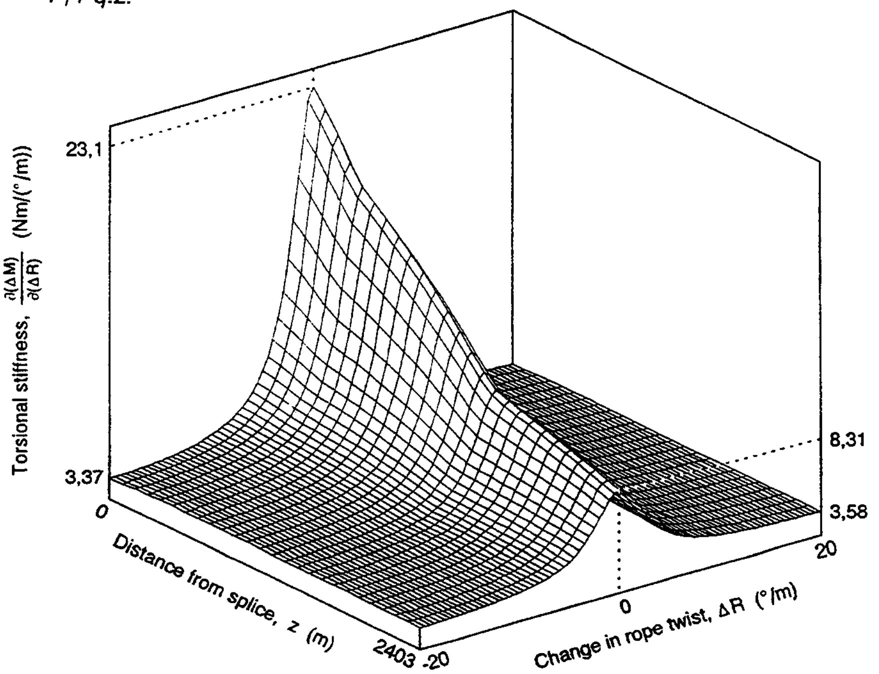

Figure 10: Variation in torsional stiffness for changes in twist from a stationary position, determined from the data in Figure 9.

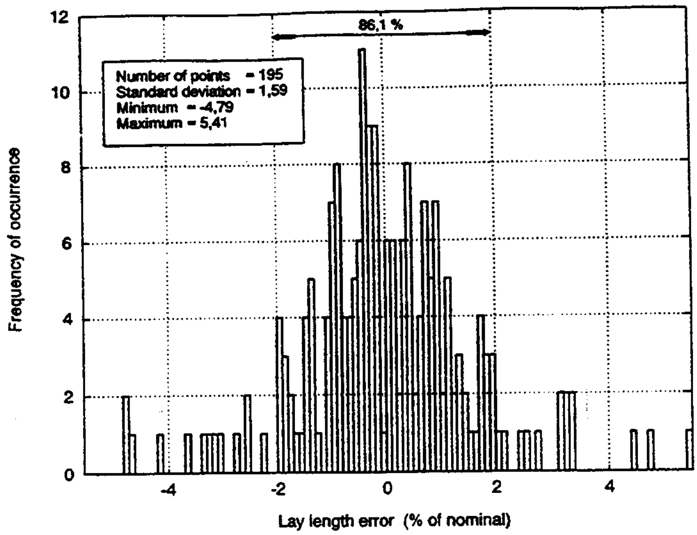

Figure 11: Distribution of errors between the calculated (LL_e) and measured lay lengths for all the ropes examined.

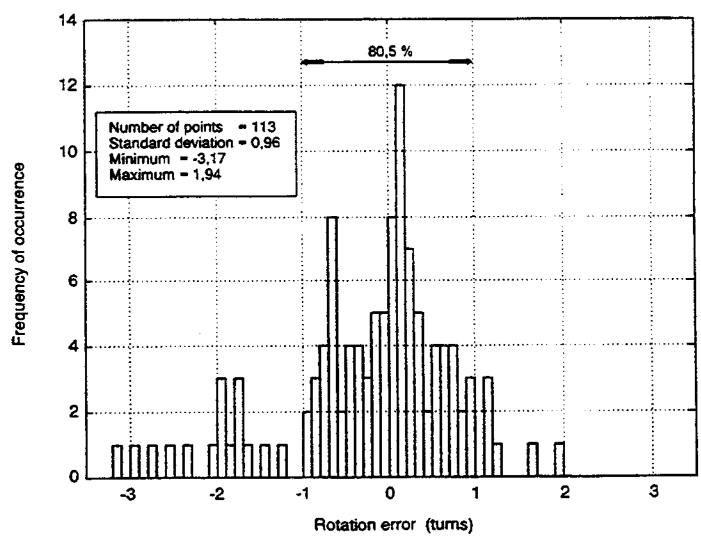

Figure 12: Differences between the calculated ($\Delta\phi$) and measured rotations for all the ropes examined.

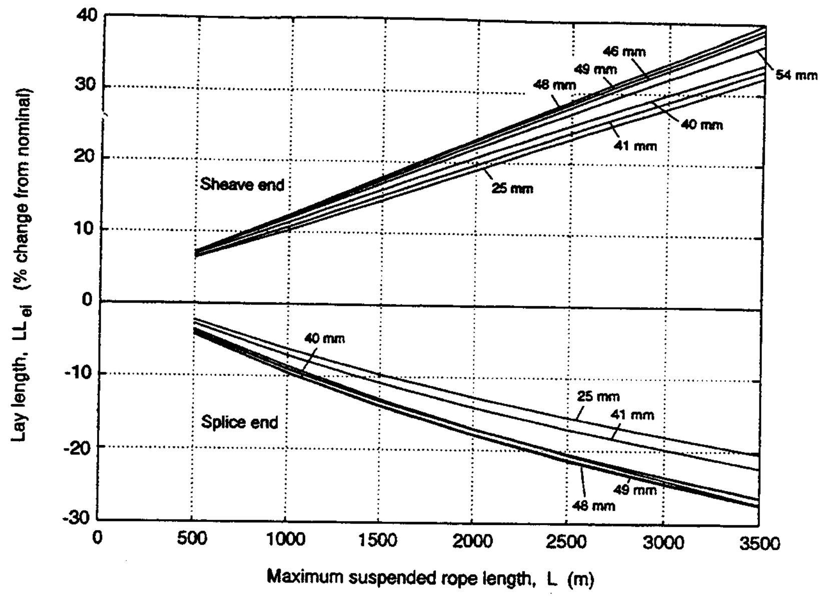

Figure 13: Calculated variation in splice and sheave end lay lengths at installation for different rope diameters and shaft depths, $z_{max} - L = 370$ m, $LL_m = 1{,}0371.LL_{nom}$, ratio of conveyance weight to payload = 0.68. Load carrying capacity according to equation (10).

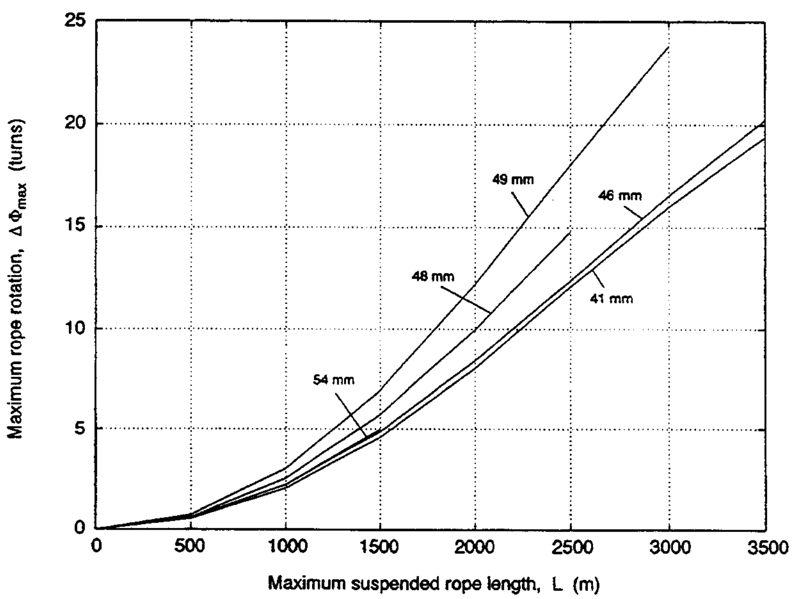

Figure 14: Calculated variation in the maximum rope rotation during conveyance loading at installation for different rope diameters and shaft depths, $z_{max} - L = 370$ m, $LL_m = 1.0371.LL_{nom}$, ratio of conveyance weight to payload = 0.68. Torsional stiffness data not available for the 25 mm and 40 mm ropes.

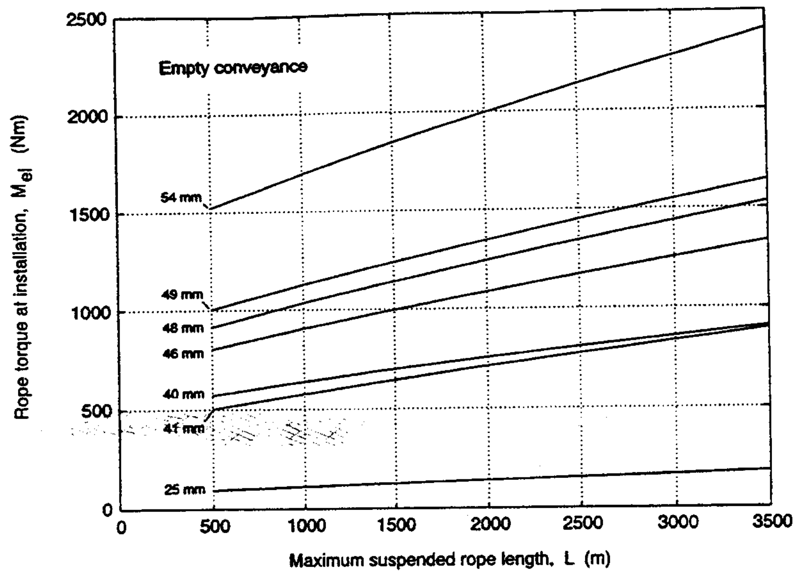

Figure 15: Calculated variation in rope torque for different rope diameters and shaft depths at installation. $z_{max} - L = 370$ m, $LL_m = 1.0371 LL_{nom}$, ratio of conveyance weight to payload = 0.68. There was a slight difference in the test method for the 40 mm rope.

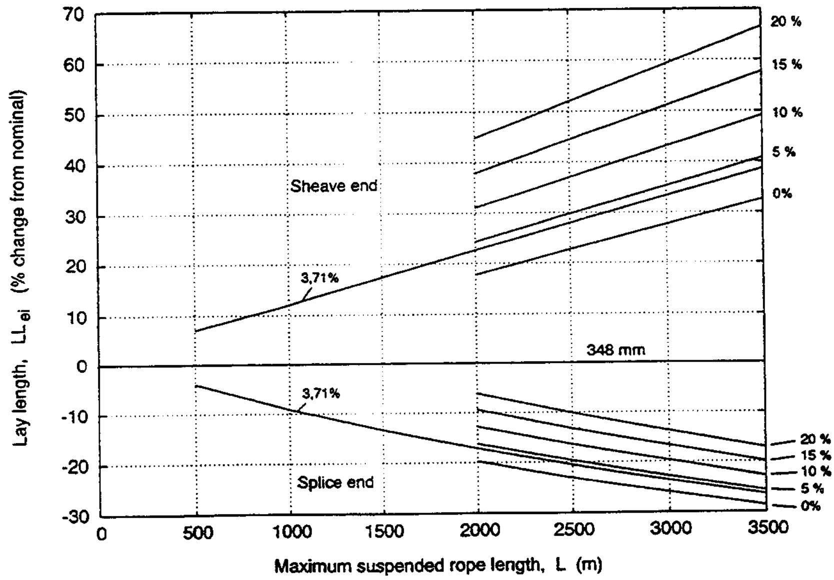

Figure 16: Calculated variation in splice and sheave end lay lengths for changes in the manufactured lay length at different depths. In all cases, the % values indicate the increase in LL_m from LL_{nom}, 46 mm rope only, $z_{max} - L = 370$ m, ratio of conveyance weight to payload = 0.68. The closing specification range is usually 0 % to 5 %.

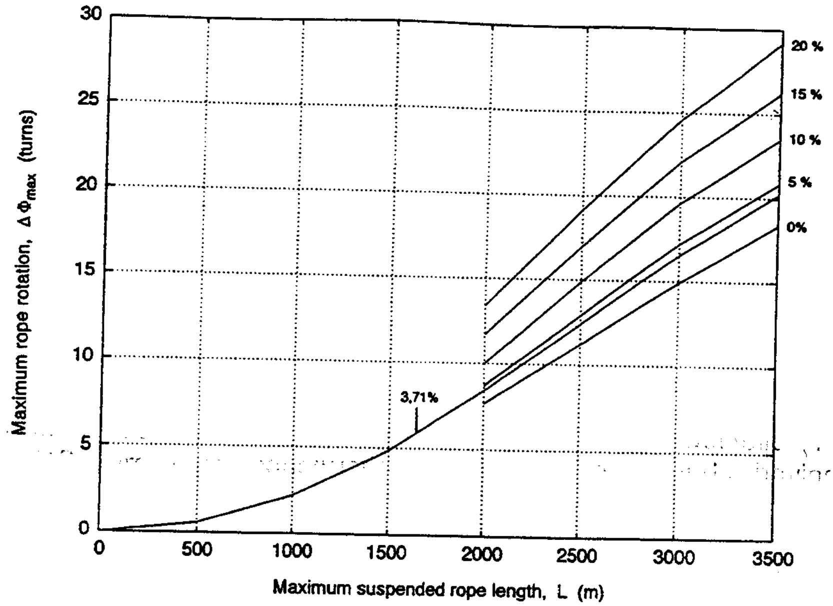

Figure 17: Calculated variation in the maximum rope rotation during conveyance loading for changes in the as-manufactured lay length at different depths. In all cases, the % values indicate the increase in LL_m from LL_{nom}, 46 mm rope only, $z_{max} - L = 370$ m, ratio of conveyance weight to payload = 0.68.

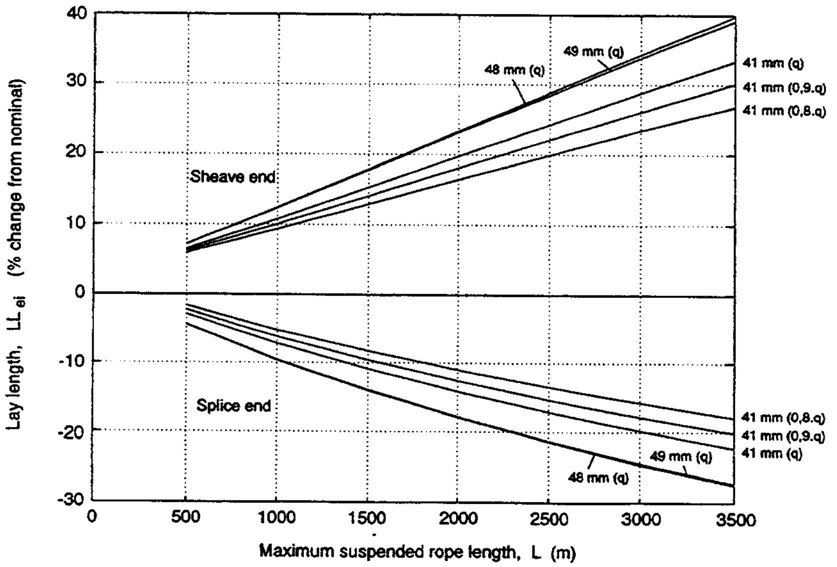

Figure 18: Calculated variation in splice and sheave end lay lengths for changes in rope weight per unit length, $z_{max} - L = 370$ m, ratio of conveyance weight to payload = 0.68, q = nominal weight per unit length.