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RESPONSE OF BURIED POWER TRANSMISSION CABLES TO EARTHQUAKE-INDUCED TRANSVERSE PERMANENT GROUND MOVEMENT

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ABSTRACT

The aim of this paper is to assess the response of the buried power transmission cables to transverse permanent ground deformation (PGD). In order to accomplish this, the results of full-scale experimental studies in conjunction with continuum nonlinear finite element analyses were first used to define the cable-soil interaction behaviour as nonlinear springs. Numerical models were then developed to evaluate the response of buried power transmission cables to the width and the amount of ground deformation. The analytical formulations supported by numerical analysis were used to express the developed force and displacement in the cable as a function of cable mechanical properties, cable/soil interaction behavior, and the PGD parameters. With the aid of analytical formulations, the threshold ground deformation causing a yield in the cable and causing the maximum cable deformation were identified. Those two threshold ground deformations will assist the utility owners in quick assessment of the response of the buried power transmission cables.

Introduction

Power transmission industries rely on a large network of subterranean, submarine, and overhead transmitting lines to transfer electricity from the power plant to users, and they need to maintain a high level of reliability during emergencies, such as earthquake events. With the increased use of high voltage underground cable technology (550 kV and 230 kV), utility owners need guidelines to asses the performance of the existing buried cables, and also to design the buried cables for seismic events. Current knowledge on the response of buried power cables in seismic events is scarce although there may be some findings from investigations performed by private entities for specific uses that are either not published, or cannot be generalized to other conditions. Although guidelines such as ASCE (1984) and ALA (2001) are available for buried steel or polyethylene pipelines they are not directly applicable to the buried power transmission cable due to the following reasons. Firstly, the cables have mechanical/structural properties that are different from those of the steel or polyethylenes pipelines commonly used in developing those guidelines, in terms of their bending flexibility and axial rigidity. Secondly, the power cables are typically buried in “thermal backfill” material which is significantly different from sandy material most commonly used in those guidelines, in terms of density, dilation angle, and

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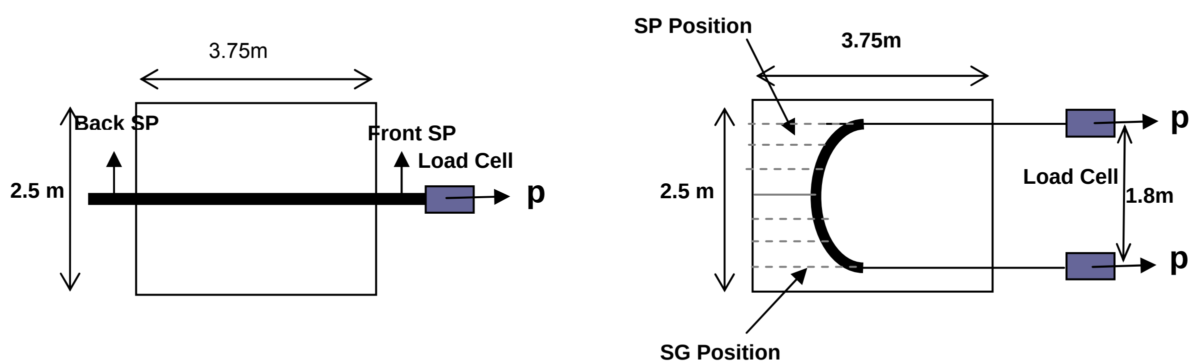
friction angle. There is a critical need to establish the tool and the framework necessary to evaluate the seismic response of the buried cable structure. This paper is response to these needs by analyzing the realistic case of buried power transmission cables. This aim is accomplished by, first characterizing the soil/cable interaction by nonlinear springs in the longitudinal and transverse directions, then analyzing the buried cable response to transverse permanent ground deformation, and finally developing the analytical formulation for quick response analysis of the cable to the transverse permanent ground deformation events.

Idealized Soil Response Model for the analysis of Cable-Soil Interaction

In order to characterize the cable/soil interaction behaviour, full-scale experimental studies were conducted at the University of British Columbia (UBC). In the experimental tests, two sets of tests were performed to obtain soil restraints in the longitudinal and horizontal transverse directions as shown in Figure 1. A total of 15 axial pullout tests and 10 lateral pullout tests were conducted on the cable with different burial depths. More details of tests, used material, and testing procedures can be found in Ahmadnia et al. (2008). Targeted laboratory element testing was also conducted to characterize the shear response of thermal backfill material and the shear response of thermal backfill/cable interface. The estimated average peak friction angles (ϕ'_{max}), from direct shear testing, for the three soil densities (dense (1.79 g/cm^3), medium ((1.60 g/cm^3), and loose (1.39 g/cm^3)), are about 59°, 53°, and 44° respectively. The large–strain friction angle during direct shear test (ϕ'_{cv}) is 42°. The interface friction angle factor (f) which is defined as a fraction of interface friction angle (ϕ) to soil internal friction angle (δ) is obtained as 0.63. The buried cable is designated as a 230 kV power cable with a diameter of 10 cm. Simple compression tests and three-point bending tests were conducted to get the axial deformation and curvature deformation of the cable as shown in Figure 2. Figure 3 shows the summary results of the axial and lateral pullout tests for a cable with different burial depth. These test results are used to characterize the cable/soil interaction behaviour.



a) axial pullout t test

b) lateral pullout t test

Figure 1 . Schematic diagram showing typical test set up: a) axial pullout test, b) lateral pullout test (SP=String Potentiometer, SG=Strain Gauge)

In practice, the soil/cable interaction behaviour is commonly represented by nonlinear springs. This representation method is more desirable in the seismic response analysis of the buried cable since the seismic analysis often involves a large number of sensitivity analyses; thus, nonlinear spring provides a fast analysis tool in compared to other alternative methods such as three-dimensional continuum nonlinear analysis. The nonlinear springs idealize the soil restraints as a function of the cable/soil relative movement in three independent directions as shown in Figure 4. The characteristic behavior of the spring models must be defined so as to represent the media surrounding the buried cable adequately in a simple mathematical term. The next section describes the approach to define the characteristics of the longitudinal and horizontal transverse nonlinear spring model.

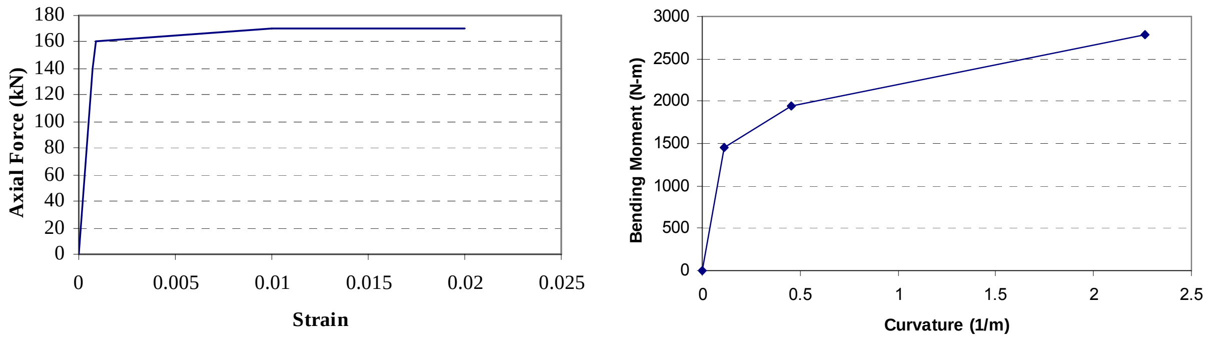


Figure 2: The mechanical properties of the buried power transmission cables, axial-strain behaviour (left), moment-curvature behaviour (right)

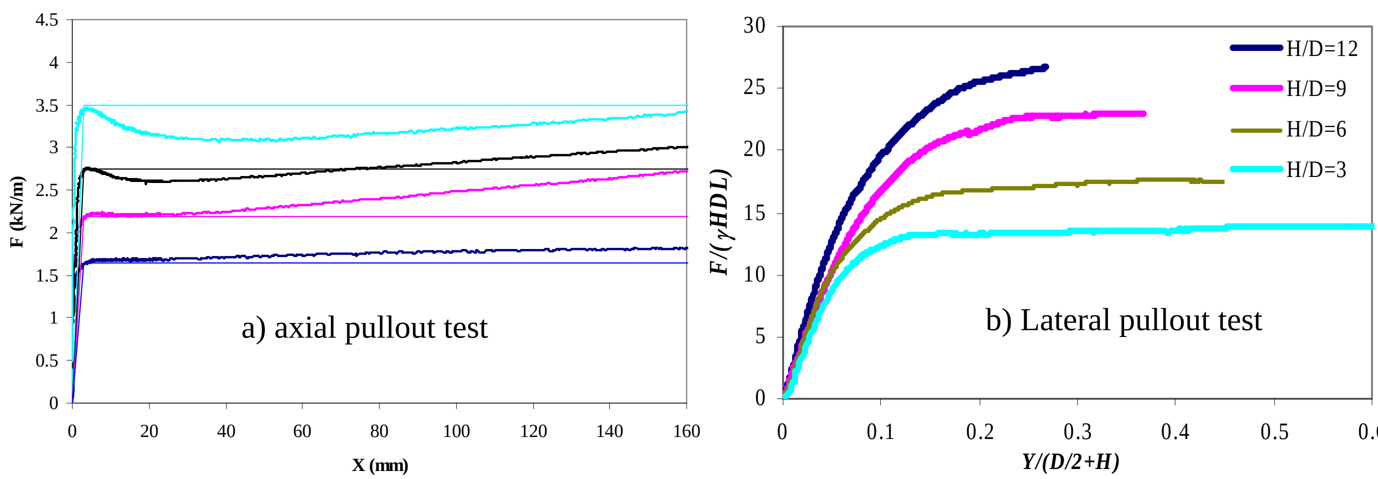


Figure 3. *a*) load-deformation curves and bilinear representations of the longitudinal soil spring for the buried cable in the axial pullout test and *b*) load-deformation curves for the buried cable in the lateral pullout tests.

Representation of spring behaviour in the longitudinal direction

The constitutive behavior for a cable-soil interaction in the longitudinal direction can be obtained from the axial pullout test results. The axial pullout response of the buried cable is generally influenced by two important factors (the shaft friction and the normal stresses on the buried cable) as shown in Figure 3-a. The shaft friction characteristic depends on the interface interaction of the two contacting objects which can be obtained empirically. The normal stress distributions on the buried cable are varied depending on the static or kinetic conditions. In the static state, it depends on the burial depth ratio and also on the flexibility of the buried cables to the surrounding environment. In the kinetic state where a relative soil/cable movement exists, the dilation of the dense soil at the buried cable soil interface, as observed by Wijewickreme et al. (2008) in steel pipeline, and also the out-of-straightness of the buried cable (small camber in the buried cable) influence the normal stress distribution from the static conditions. The observation that the leading and the tailing ends of the buried cable during axial pullout test move together indicates that the longitudinal soil restraint is mobilized simultaneously along the buried cable. Thus, the constitutive behavior of the longitudinal soil spring can be simply derived from the experimental tests by matching a bilinear curve as shown in Figure 3.

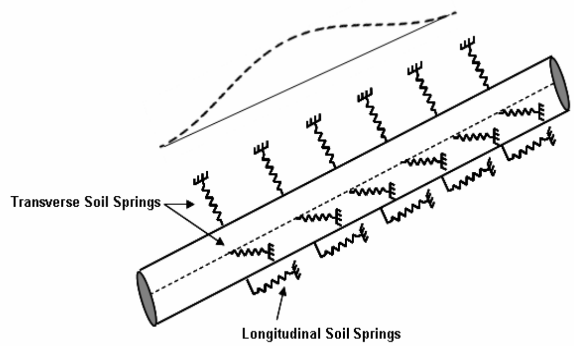
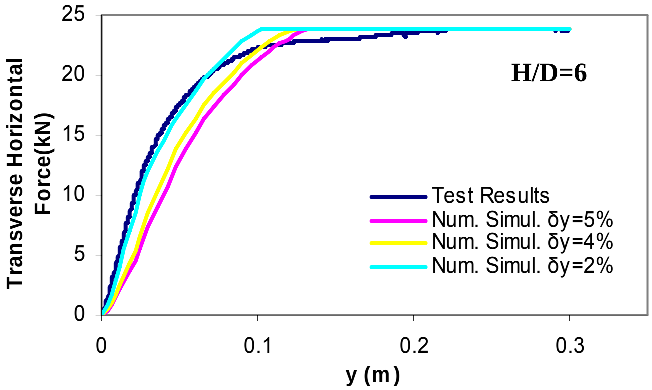


Figure 4. The idealized soil/cable interaction representation at the buried cable interface

Representation of spring behaviour in the transverse direction

The constitutive behavior for a cable-soil interaction in the horizontal direction can be obtained from the lateral pullout test results. To define a nonlinear constitutive model, a bilinear model is assumed. The unknown coefficients of the soil spring, the yield force, the yield displacement, and the hardening slope, were obtained by the curve fitting technique. First in this method, the behavior of the cable in terms of the moment-curvature (M-φ) and the axial-deformation (N-ε) relationship were characterized. Second, the unknown coefficients were calculated by creating the best match between the response of the buried cable and the experimental studies. This procedure was performed with the commercial software ABAQUS standard Ver. 6.7-1 (2007) for the cable with the burial depth ratio (H/D=3, 6, 9, and 12). The pipe-soil-interaction (PSI) element was used to model the interface behavior, and bilinear constitutive model was selected for its behavior. The (M-φ) and (N-ε) relationships, as shown in Figure 2, were used for the mechanical properties of the buried cable. The problem with different bilinear models was analyzed by subjecting the cable ends to the same amount of the displacement as used in the experimental studies through nonlinear static analysis with large deformation option. Figure 5 shows the force-displacement relationship from different bilinear models and the force-displacement of the experimental studies for burial depth ratio of 6. The table in Figure 5 shows the final selection of the bilinear model parameters for the bilinear model as a function of the burial depth.



D (cm)	H (cm)	H/D	Nq	δy	δy/H
10	30	3	14.2	0.01	.033
10	60	6	18.4	0.02	.033
10	90	9	21.5	0.03	.033
10	120	12	26.8	0.035	.029

Figure 5. The result of the calibration of the horizontal transverse spring model for *H/D*=6, and the summary table of the bilinear representation for different burial depths.

Analyze the response of buried cables subjected to the transverse PGD

Seismic risk assessment of the buried cable involves identifying the seismic hazards and evaluating the buried cable response to those hazards. Seismic hazard to the buried cables can result from either the transient ground deformation (TGD) or the permanent ground deformation (PGD). TGD refers to the vibration of the ground caused by seismic wave propagating. PGD refers to the ground movement caused by the fault movement or liquefaction induced lateral spreading. PGD was observed as a significant hazard for the buried pipeline (Liu and O'Rourke (1997)). On the other hand, the flexible nature of the buried cables suggests that during seismic wave propagation they can accommodate the ground deformation; thus, the TGD will not be the major hazard to them. PGD zones are characterized by their shape, amount of the ground deformation (δ), and width (W). Every PGD can be decomposed into two perpendicular directions, longitudinal direction and transverse direction. The longitudinal PGD refers to the relative buried cable-ground deformation in the buried cable alignment, and transverse PGD refers to the relative buried cable-ground deformation in the perpendicular to the buried cable alignment. This paper describes the behavior of completely straight buried power transmission cable subjected to the transverse PGD. Different patterns of the PGD have been proposed by different researchers (Liu and O'Rourke (1997)). Herein, the cosine function to the power of 2 was used as the pattern of the ground deformation as described below:

$$D(x) = \delta \cos^2 (\frac{\pi x}{w}) \qquad (1)$$

This function is symmetric at the center with the maximum of ground deformation (δ), and tangentially approaches to zero at its margins ($x = \pm w/2$). The amount and the width of ground deformation can be identified by the seismic hazard analysis of the region. Commonly, the width ranges from 10 to 50 (m) and the amount of ground deformation can be as high as 2-3 (m).

Description of numerical simulation of the buried cable subjected to the PGD

Two cables with the burial depth ratio of 6 and 10 were selected for the analysis. The cable structure has the same mechanical properties as the one used in the experimental studies of lateral pullout tests. The analyses were performed by the finite element program ABAQUS 6.7-1. The PSI element was used to model the interaction behavior between the cable and the soil. The constitutive behavior in the longitudinal and transverse directions was assumed as the bilinear behaviour as described in the previous section. The nonlinear general beam section was used to define the moment-curvature (M-φ) and the axial-deformation (N-ε) relationship of the buried cable. The cable was modeled as a continuous long beam with the mentioned mechanical properties. The length of the cable was long enough to not influence the result of the analysis due to the boundary conditions. In every analysis, strains at the ends of the cable were checked to confirm that the strains were small enough to make sure the location of anchor points were not influencing the analysis results. The ground deformation was applied to the other end of the PSI element to simulate transverse PGD. By keeping the pattern of the ground deformation constant and by increasing the amount of the ground deformation gradually and monotonically, the nonlinear responses of the buried cable were conducted.

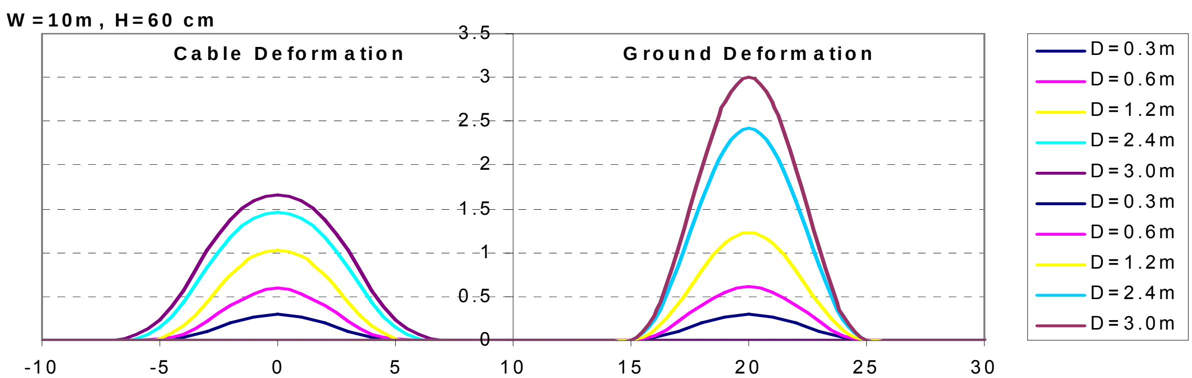


Figure 6. Ground deformation and corresponding cable deformation subjected to the transverse PGD with the width of 10 m (W=10m)

The primary objective of this section is to gain an understanding on the parameters that influence the performance of the buried cable. The cable performance is expected to be influenced by, 1) cable mechanical properties, 2) the soil/cable interaction behavior, and 3) the transverse PGD deformation parameters. This study focuses mainly on the effects of the ground deformation parameters; namely the amount of the PGD and width of PGD zones (*W* and *D*). The analytical formula was followed by the numerical simulation for a general form of the soil-cable interface and different cable mechanical properties. The effect of the ground deformation intensity on the buried cable performance was studied by increasing the amplitude of the ground deformation (*D)*. The analyses show two noteworthy behaviors. The first observation relates to the buried cable deformation as the ground deformation intensity increases. As shown in Figure 6, at small ground deformation amplitude, the buried cable deforms to the shape of the ground deformation until the buried cable becomes taut. Because of the small bending stiffness of the buried cable, the resistance to any significant lateral deformation is achieved by the tensile force development from the slack state to the taut state. After achieving enough tautness, the buried cable does not conform to the ground deformation pattern by creating resistance to the lateral ground deformation and finally approaches its plateau (D_{pl}). The second observation relates to the development of forces/moments and displacements during the ground movement. As buried cable deforms, the axial and curvature strains are developed in the buried cable. Figure 7 shows the axial force development in the cable as a function of the amount ground deformation for five levels of intensity (D=0.3, 0.6, 1.2, and 3.0 m). As shown, the pattern of the axial force remains unchanged after reaching a certain intensity level. Also, the same trend is observed with the axial deformation development in the buried cable to the different ground deformation intensity. Those two observations can be elucidated further by analytically analyzing the buried cable response due to the transverse PGD.

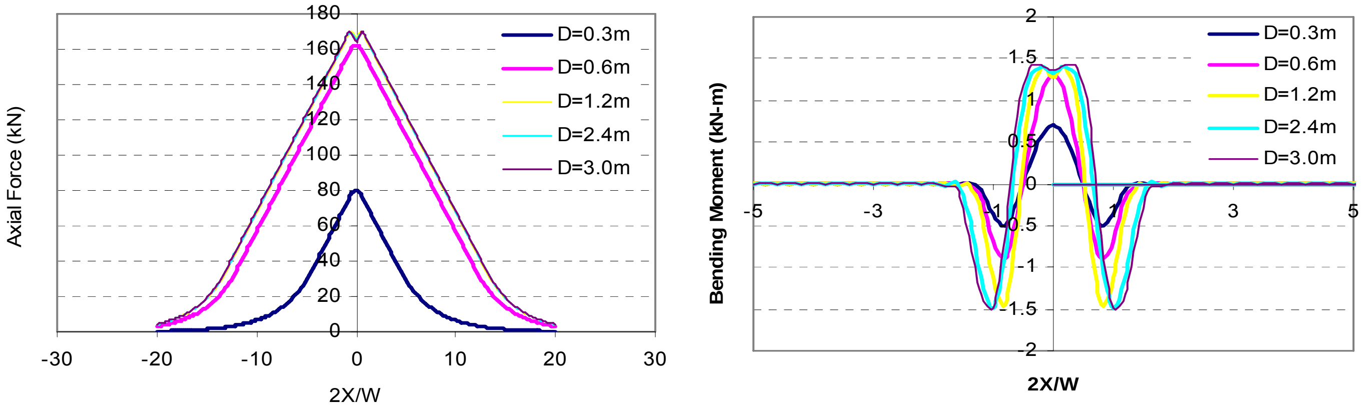


Figure 7. Axial force and bending moment development in the buried cable at different ground deformation levels

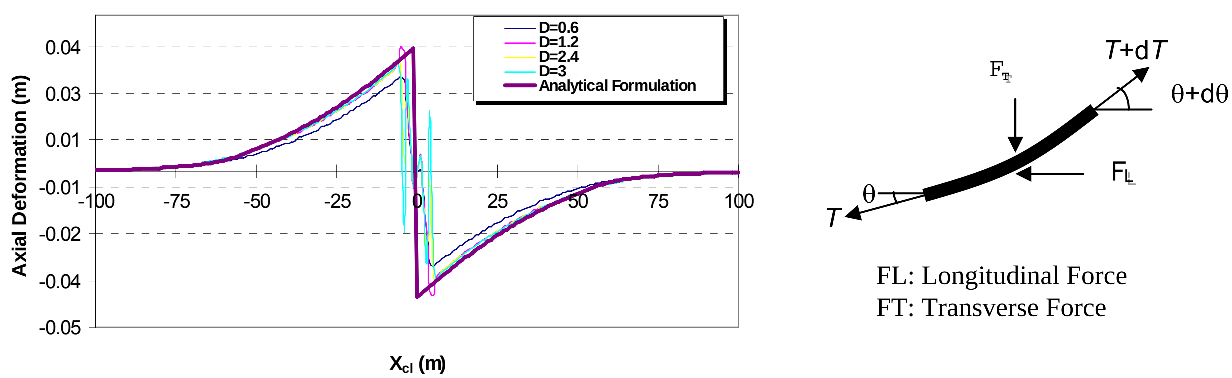


Figure 8. Verification of the proposed formula to predict the axial deformation development in the buried cable (left), and the forces acted on the small portion of the cable(right)

Description of the analytical formulations

As observed in the numerical analysis of the buried cable, there are two existing critical ground deformations that influence the buried cable response. The first ground deformation relates to the outset of the yielding in the buried cable. In order to find this ground deformation, the formation of the axial force and axial deformation due to the transverse ground movement must be investigated. The symmetric condition of the problem causes the formation of the maximum tensile force and maximum axial deformation at the cable centerline, and the first yield will consequently form in this location at the certain ground deformation (D_y). By referring to Figure 8 for equilibrium of the small piece of the cable, the axial force and axial deformation can be formulated as a function of the yield characteristics of the cables and interface soil/cable interaction behaviour as

$$T(x) = \begin{cases} T_{\max} - f_L x & \mathrm{x} < \mathrm{x_T} \\ T_1 e^{-k_g (x - x_T)} & \text{otherwise} \end{cases} \qquad u(x) = \begin{cases} u_{\max} - \varepsilon_y x + 0.5 k_g^2 \delta_{yl} x^2 & \mathrm{x} < \mathrm{x_T} \\ \delta_{yl} e^{-k_g (x - x_T)} & \text{Otherwise} \end{cases}$$

$$x_T = (\frac{T_{\max}}{f_l} - \frac{1}{k_g}), \quad T_1 = \frac{F_l}{k_g}, \quad k_g = \sqrt{\frac{F_l}{\delta_{yl} AE}}, \quad U_{\max} = \varepsilon_y x_T + (1 - 0.5 k_g^2 x_T^2)\delta_{yl} \tag{2}$$

In which F_l, δ_{yl} are the longitudinal yield force and yield displacement, T_{max} ,ε_y are the axial yield force and yield strain respectively. Figure 8 shows a good agreement of the developed analytical formula for the axial tensile force and axial deformation with those obtained from numerical simulations As can be seen, although the buried cable is subjected to the transverse PGD, the formulation of the axial force and deformation are expressed as a function of the longitudinal soil restraint and axial characteristics of the buried cable. With the knowledge obtained from numerical simulation that the plastic yielding occurs at small ground deformation, the amount of the ground deformation creating the yielding in the buried cable can be obtained by

$$\frac{\pi^2 D_y^2}{8W} = u_{\max} \rightarrow D_y = \sqrt{\frac{8W}{\pi^2} u_{\max}} \tag{3}$$

Further increase in the amount of ground deformation ($D>D_y$) leads to the concentration of axial strain in the cable centerline and developing the plastic link length. After certain ground deformation, as shown in numerical simulation, the cable does not conform to the ground deformation and it eventually yields to its maximum deformation. Identifying the second critical ground deformation level (D_{pl}) has an important feature in the buried cable performance evaluation since it indicates that for the ground deformation ($D>D_{pl}$) cables reaches their final configuration and consequently the axial force and displacement will not increase.

The numerical analysis of the buried cable shows that the buried cable deformation zones are just not limited to the PGD zone, and it extends beyond the PGD width (W). Calculating the relative deformation of the ground and that of the cable shows that the ground deformation lags behind the cable deformation after x=0.6(W/2) from the buried cable centerline, these two regions are shown as “thrust” and “heave” zones in Figure 9. The “thrust and heave” zones are required to happen irrespective of the assumed shape of the ground deformation to balance out the exerted forces on the buried cables. The equation to formulate the buried cable deformation shape can be formulated as

$$\frac{d^2 y}{dx^2} = \frac{F_T(x)}{T(x)\cos(\theta)} = \frac{F_T(x)}{T_{horizontal}} \tag{4}$$

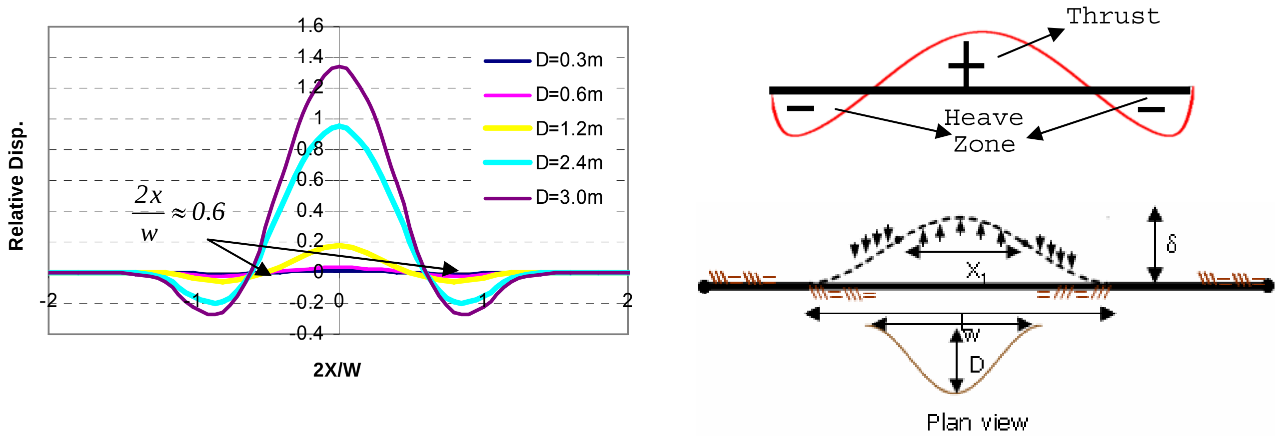


Figure 9. The relative deformation of the ground and the buried cables and the formation of the "thrust" and "heave"

In which $F_T(x)$ is the horizontal transverse soil restraint and $T(x)$ is the tension force. By knowing that the transverse soil restraint will be yielded when the deformation is large and by assuming the average tensile force reaction, the height (h) of the "thrust" and "heave" zones can be calculated according to the following

$$h = \frac{F_T(2X_1)^2}{8\overline{T}} \tag{5}$$

Figure 10 illustrates the schematic representation to calculate the (h) value and the maximum cable ground deformation ($D_{pl}=h_1+h_2$). Figure 11 shows that the analytical predictions of D_{pl} for the cable with the burial depth of 6 and 10 are in the good agreement with those obtained from numerical analysis.

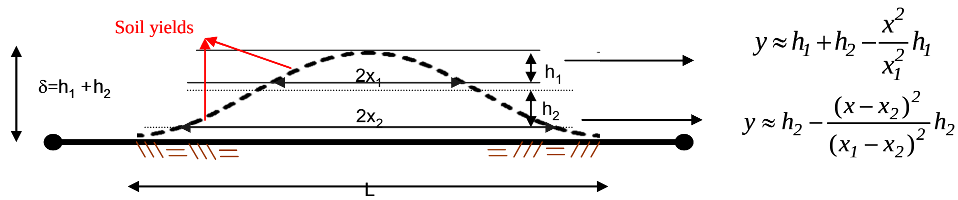
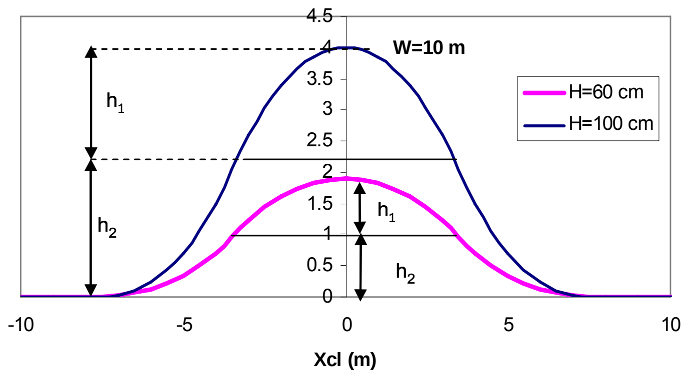


Figure 10. Analytical formula representation of the plateau deformation

Discussion and Conclusion

The results of the full-scale testing were used to idealize the soil/cable interaction with the bilinear behvaiour in the longitudinal and the horizontal transverse directions. The results of the numerical simulation of the buried power transmission cable subjected to several transverse PGDs were used to develop the analytical formulations. The results of the numerical analysis show that by introducing two levels of ground deformations (D_y, D_{pl}), the cable response can be characterized. For the amount of the ground deformation ($D<Dy$), the buried cable will operate in the elastic range. When the amount of the ground deformation approaches ($D=D_y$), the first

yield in the buried cable will form. For the amount of the ground deformation (*Dy<D<Dpl*), the plastic link is formed and developed with maximum strain concentration in the plastic link. For the ground deformation (*D ≥Dpl*), the cable reaches to its maximum deformation and strains do not vary with further increase in the ground deformation. The result of numerical simulation indicates that in the estimation of D_y, the longitudinal characteristic of soil restraint is more important. Analytical formulation was presented to express D_y as a function of the longitudinal soil restraint, axial properties of the buried cable, and the width of the PGD zone. On the other hand, in the estimation of the *Dpl*, the horizontal transverse characteristic of the soil restraint is more important, and analytical formulation was developed as a function of the horizontal soil restraint, tensile force and width of ground deformation.



	H=60,h_1	H=60,h_2	H=100,h_1	H=100,h_2
T (kN)	150	140	150	140
Ft (kN/m²)	22.1	22.1	47.2	47.2
L (m)	6	7	6	7
h_1 or h_2	0.66	1.26	1.4	2.69
$\delta=h_1+h_2$		1.92		4.11

Figure 11. Verification of the proposed formula to predict the maximum cable deformation (D_{pl})

Acknowledgement

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