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Response of Buried Power Transmission Cables to Earthquake-induced Permanent Ground Deformations

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ABSTRACT :

The performance of buried power transmission cables in areas subjected to ground deformations is an important engineering consideration for the utility owners. The performance of buried power transmission cables subjected to permanent relative axial ground displacements was investigated using a full-scale testing facility. The facility comprises a 2.5 m x 3.8 m soil chamber, with the capacity to subject buried transmission cables (or pipelines) to large relative displacements. The buried cables were subjected to relative axial and transverse soil movements, and the test results are compared with the response predicted from commonly used approaches to assess the performance of buried pipelines. The peak loads under relative axial soil movements on cables buried in dense soil were noted to be under-predicted by the current approaches; this is likely due to the increased soil normal stresses on the cable due to constrained soil dilation not accounted by the current approaches. The general trend of the predicted response using current approaches for pipelines under lateral loading is in reasonable agreement with the experimental observations, although direct comparisons between the test results and the predictions were difficult due to the three-dimensional cable deformation patterns arising from lateral loading tests.

KEYWORDS: Soil Cable Interaction, Ground Deformations, Power Transmission Cable

1. Introduction

With increased use of below-ground transmission cables for transmission of electrical power, the performance of below-ground transmission systems in areas prone to ground movements is an important engineering consideration for the utility owners since the failure of such systems could cause property damage and loss of human life, in addition to the invariably associated business disruption. Permanent ground displacement (PGD) might result from creeping ground, landslides, slope instability and earthquake-induced movement including lateral spreading or fault movement. Liquefaction due to seismic loading and rainfall-induced slope instability (with or without earthquakes) are among some common causes of potential ground movements, and large differential ground movements can lead to unacceptable strains in below-ground cables. A thorough understanding of the cable-soil interaction becomes critical in the evaluation of the performance of power transmission cables when subjected to ground movements; the composite construction of the cables (i.e., a cross-section with protective/insulating sheathing around copper conductors) further adds to the complexity of evaluating the strains and the determination of criteria for acceptable performance.

Current knowledge on the response of buried power cables subject to ground movement is scarce although there may be findings from investigations performed (by private entities) for specific uses that are either not published and documented, or cannot be generalized to other conditions. Due to this lack of alternative approaches, pipe-soil interaction models developed for steel pipes (ASCE 1984, ALA 2001) are considered to provide an approach for analyzing cable configurations. Data from controlled experimental work on cables subject to axial movement, particularly conducted at full-scale level, is needed to advance the knowledge of the response of buried cable systems subject to ground movement.

With this background, a detailed research program involving full-scale experimental studies has been undertaken at the University of British Columbia in partnership with British Columbia Transmission Corporation (BCTC) to study cable-soil interaction during permanent ground deformation. The objective of these experimental researches is to simulate the effect of PGD on cables and to determine the contributing factors influencing the associated cable-interaction. The work provides an opportunity to examine the feasibility of using the approaches developed for the assessment of pipelines (e.g., ASCE (1984)) for the assessment of buried transmission cables. This paper presents some experimental findings from full-scale tests conducted on buried cables; comparisons are made between experimentally observed soil loads on cables with those estimated from currently approaches to assess soil loads on pipelines subject to relative axial movements.

2. Experimental Setup

2.1. Experimental Apparatus

A testing apparatus that was designed and constructed at the University of British Columbia (UBC), Vancouver, Canada to conduct full-scale modeling research on pipe-soil interaction problems (Anderson et al., 2005; Weerasekara and Wijewickreme 2008) was used for the present testing work. The test setup mainly comprise of 3.8m (L), 2.5m (W), and 2.5m (H) soil chamber, hydraulic actuator system, and a data acquisition system. The apparatus can simulate the typical relative axial and lateral soil movements encountered under field ground movement situations with the ability to vary burial depth, density, and rate of different soil movement. The design of the chamber permits providing up to 2 m of soil cover above the test cables/pipes.

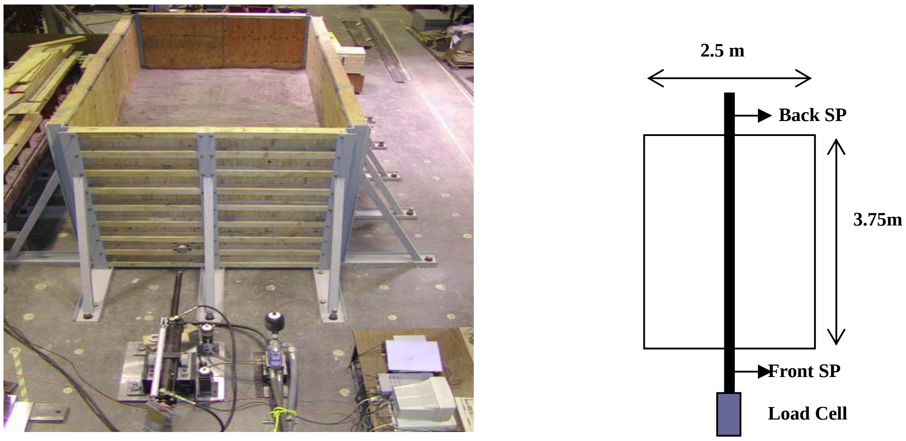
Typical cable layout configurations for lateral and axial pullout tests on transmission cables are shown in Figure 1. The soil chamber is designed to allow full development of active and passive soil wedge in lateral pullout test and to minimize the boundary effects in axial pullout test (Karimian 2006). In axial and lateral pullout testing, the transmission cables are aligned parallel to larger and shorter chamber dimensions, respectively. The tests were conducted with cables pulled out in a displacement-controller manner with a servo-hydraulic actuator having a capacity of 220 kN. The rates of displacement were set at 3.6 cm/hr for both axial and lateral pullout tests.

2.2. Material Tested

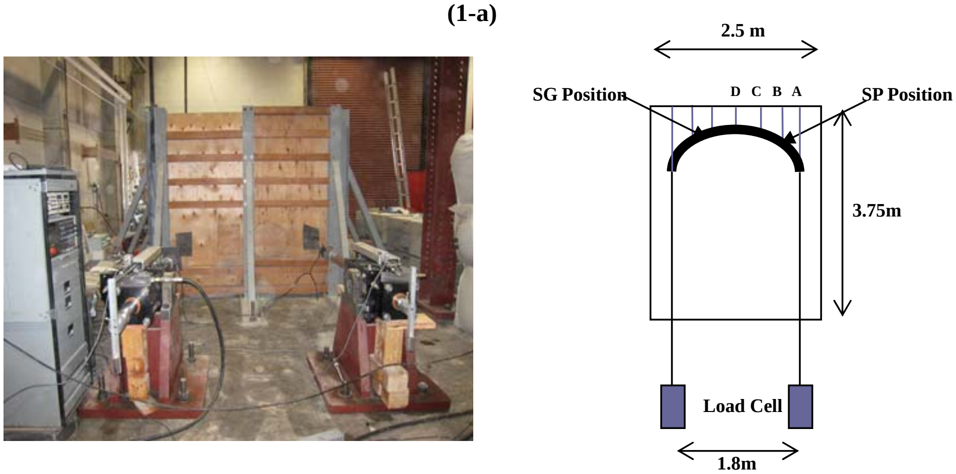
2.2.1 Backfill Soil

The pullout tests were conducted on cables buried in backfill soil (called “thermal backfill”) provided by BCTC, and the material is identical to that commonly used in the field installations by BCTC. The envelope (limits) of grain size distribution for backfill soil specified by BCTC for their field applications is given in Figure 2. The gradation curve derived from a grain size distribution test conducted on a backfill sample of the soil used in the pullout testing program is overlain for comparison; as may be noted, the grain size distribution of thermal backfill material used for testing is well within the allowable limits specified by BCTC. The modified Proctor test indicated a maximum dry density of 21.7 kN/m^3 with 6.7% as the optimum water content.

Drained direct shear testing indicated that internal friction angle (ϕ) of dry material under peak and ultimate shear stress conditions are 33 and 29 degrees, respectively. In addition, interface direct shear test conducted between the backfill soil and a coupon of the cable outer layer (sized to fit the bottom part of the direct shear test) yielded an interface friction angle (δ) of 18 degrees. 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 0.55.



(1-a)



(1-b)

Figure 1 Photograph and schematic diagram showing typical test set up for: (a) axial pullout testing; and (b) lateral pullout testing (SP= String Potentiometer, SG=Strain Gauge)

In preparation of the specimens for testing, backfill material was placed under moist conditions. An approximate target moisture content of 3 to 4 % was achieved by sprinkling water over each lift of material placed in the soil chamber. In all tests, the backfill soil was placed in 100 mm thick layers at a given time, and the material was compacted using ½-tonne static roller. The resulting average soil density of backfill material for all the tests was 20.3 kg/m3. The density readings were obtained with density measurements using: (i) sand bowls placed in the soil chamber during soil placement and compaction; and (ii) calculations based on the overall mass of soil placed during a given test.

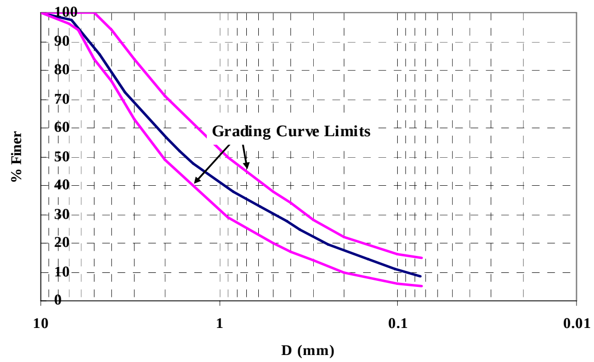
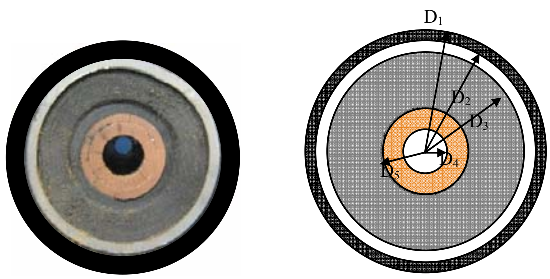


Figure 2 Grain size distribution of tested backfill soil along with specified limits

2.2.2 Power Transmission Cable

The power transmission cables for testing were provided by BCTC. The tested cables are self contained oil filled (SCOF) copper conductor with impregnated paper insulation protected by carbon black tape shielding and aluminum sheath. A typical cross-sectional configuration of the tested transmission cables is depicted in Figure 3.



Item	Component	Description	Thickness(mm)
1	Insulating Fluid Duct		6
2	Conductor	Self Supporting segmental strips of Copper	12
3	Insulation	Impregnated paper Tape	20
4	Armor	Aluminum Sheath	6
5	Serving	Polypropylene Protector	6

Figure 3 Power Transmission Cable Cross Section
(left: photograph; right: schematic section)

The transmission cables are designed to operate at maximum voltage of 230 kV. Two different transmission cables were employed in this research. The first type is a 900 kcmil copper conductor with the overall diameter of 89 mm (3.5 inches), which was used in axial pullout testing; the other type is 1800 kcmil cables with the overall diameter of 100 mm (4 inches) with a weight of 15 kilogram per meter unit, which is used in lateral pullout test.

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Fifteen (15) longitudinal and ten (10) transverse soil deformations were simulated in the pullout test to examine the effect of several key parameters including different burial depth, soil density, and cable configuration. Only typical results are presented and discussed in this paper.

The applied load on the cables in axial pullout tests was measured using a load cell mounted in-line to the actuator loading ram. For measuring load on the pipe during transverse pullout tests, load cells were mounted on each of the loading rams of the two actuators. Total load on the pipe in lateral load tests was taken as the sum of the load measured from each load cell. Cable displacements relative to the concrete floor of the laboratory were measured using string potentiometers. During axial pullout tests, axial pipe displacements were measured using string potentiometers located at the leading and trailing end of the pipe (see Figure 1). In lateral pullout tests, the displacement at both ends and selected locations along the cable were also measured using string potentiometers (i.e., string potentiometer locations are shown as points A, B, C and D in Figure 1-b); in this, thin steel wires were attached to the transmission cable at the desired locations, and they were passed through the soil to the outside the box and then attached to the string potentiometers. In some lateral pullout tests, strain gauges were also mounted on the cable (at the same locations as those used for the string potentiometers) to measure axial strains in the back and front sides of transmission able.

3. Results and Discussion

3.1. Current approaches for determining soil loads during relative ground displacement

Mobilization of axial soil loads on buried cables or pipes is essentially governed by the interaction that takes place at the interface between soil and cable (or pipe). The commonly used approach for determination of axial loads on buried pipes, as recommended by ASCE (1984) and ALA (2001) can also be considered for the computation of soil loads on buried cables. According to ASCE (1984) provisions, soil restraints on buried elements are represented by components in longitudinal and transverse directions, and the key equations arising from these provisions are presented in this section. The maximum longitudinal (axial) soil restraint for a fully buried line is expressed as:

$$F_{axial} = \gamma'.H.(\frac{1+k_0}{2}).\tan(\delta).(\pi.D) \qquad (3.1)$$

where F_{axial}= axial force per unit length on buried lines, D=Buried line diameter, H=depth from ground surface to pipe centerline, k_0= coefficient of lateral earth pressure at rest, δ= interface friction angle between cable and pipeline.

The ASCE (1984) approach suggests that the maximum transverse soil restraint on unit length of a buried line can be expressed by Eqn. (3.2). Furthermore, the relation between the force per unit length (P) and horizontal displacement (δ) can be expressed by a rectangle hyperbolic formulation as stated by Eqn. (3.3). The load deformation relation was initially developed to examine a passive earth pressure on vertical anchor plates and walls by Audibert et al. (1977); the method introduced by Trautmann and O'Rourke (1985) was later used as a method to calculate transverse soil restraint on the buried line as discussed in ASCE (1984) provisions.

$$P_u = N_\gamma \gamma' HD \qquad (3.2)$$

N_γ is a horizontal bearing capacity factor, a function of burial depth ratio and friction angle.

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$$\frac{P}{P_u} = \frac{\delta / D}{.15\frac{\delta_u}{D} + .85\frac{\delta}{D}} \tag{3.3}$$

δ_u is the displacement that the maximum load transfer occurred which is on the order of 0.02 up to 0.1 magnitude of (H+D/2). The high value corresponds to loose sand, whereas the low value corresponds to dense sand.

3.1. Buried Cable subjected to longitudinal ground movement

Typical observations on the response of the transmission cable to longitudinal ground movement (obtained from axial pull out testing) are illustrated in Figure 4. The results are for tests conducted with two different burial depths of 60 and 100 cm (burial depth ratios H/D=6.75 and 11.2). The force component is plotted as a dimensionless force ($F/\gamma'HDL$) against dimensionless cable movement (δ/D). A quick examination of Eqn.3.1 would suggest that the dimensionless quantity ($F/\gamma'HDL$) is a reflection of the soil normal stress and soil frictional components (i.e., K_0 and tan δ), and such presentation also provides an opportunity to effectively compare results from tests conducted at two burial depths.

As can be seen from Figure (4-a), the peak axial resistance is mobilized when the dimensionless cable movement δ/D is about 0.09. The peak axial resistances are followed by reduction of resistance; this noted initial increase followed drop of axial force is similar to those observed by Karimian (2006) during his axial pullout tests on buried steel pipes. As may be noted from Figure (4-a), the pullout resistance on cables seems to increase with further increase in axial displacement. This increase in resistance with increasing axial displacement (after the initial peak and drop) was observed in most of the axial pullout tests conducted on cables. In connection with this observation, it is worthwhile noting that most of the transmission cables had a slight initial curvature at the time of installation in the soil chamber for testing. In spite of concerted effort expended, it was not possible to remove this curvature (which is likely an artifact from being placed curved for a long time in a spool as supplied by the cable manufacturer) and straighten the cable prior to installation for pullout testing. It appears that, at larger axial displacements, the presence of the slight, inherent curvature of the cable would likely have promoted the development of some passive soil restraint in addition to the “shaft friction” - in turn, contributing to the increase in the observed axial soil resistance at larger cable movements.

The observed 1:1 slope of Figure (4-b) indicates that the tail end of the cable moved in harmony with the front end during axial pullout process. In essence, the observation confirms that the overall axial stiffness of the cable is sufficiently large to allow the cable to behave as a rigid body for the tested length.

Using the angle of interface friction (δ) obtained from direct shear testing and the axial force from pullout testing in Eqn. 3.1, it was possible to back-calculate a value for the coefficient of lateral earth pressure. The K values of 2.3 and 1.9 were back-calculated for the two tests shown in Figure 4 for burial depths of 60 cm and 100 cm, respectively. Clearly, these values suggest that average normal stresses on the cable during axial pullout are much larger than those typically estimated for coefficient of lateral earth pressure at rest using conventional approaches. It is of interest to note that these observations are similar to those observed by Karimian (2006) for steel pipes buried in dense sand, where the peak axial soil resistance observed on buried steel pipes were noted to be several-fold (in excess of 2 times) higher than those predictions from guidelines. With direct measurement of soil stresses on pipes during full-scale testing combined with

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numerical modeling, Wijewickreme et al. (2008) have demonstrated that this increase in is primarily due to significant increase of overall normal soil stresses on the pipelines as a result of constrained dilation of dense soil during interface shear deformations. It appears that the limitations in the current approaches for the estimation of axial soil loads on steel pipes in dense soils may also exist for the cables buried in dense soils. Further research is currently underway to investigate these concerns.

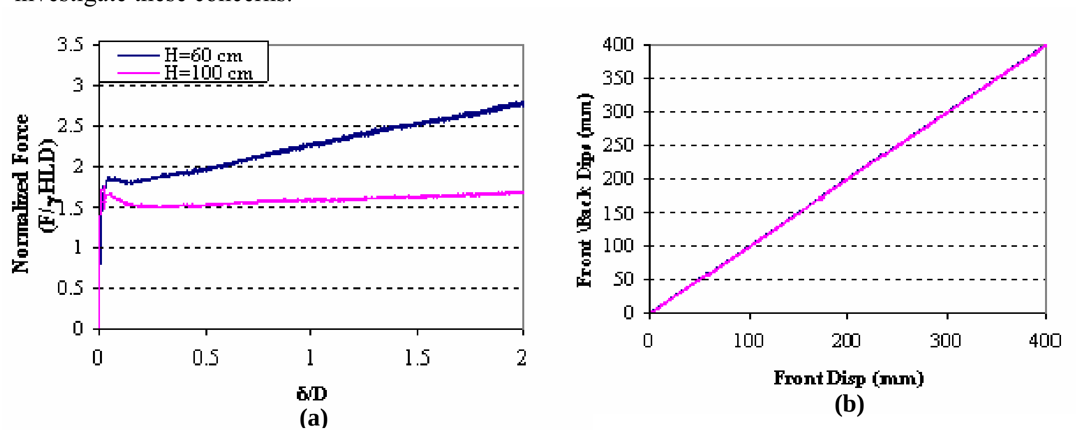

Figure 4 (a) Response of buried cable to axial pullout (Burial depths of 60 and 100 cm)
(b) Observed axial displacement of cable at the front and back ends during testing

3.2 Buried Cable subjected to Transverse ground movement

The load-deformation responses of cables during lateral pullout tests are depicted in Figure 5. Similar to the presentation of results for axial pullout tests, a dimensionless force (N_γ=F/ (γ′HLD)) which reflects a lateral bearing capacity factor is plotted with respect to dimensionless lateral displacement (δ/D). The test results presented in the figure corresponds to a cable installed at a burial depth of 0.3 m. As may be noted, the graph suggests lateral forces rises to a peak when the δ/D value reaches about 0.45.

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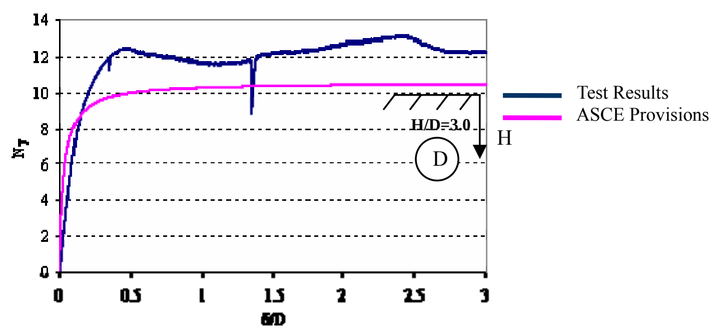

Figure 5 Response of buried cable to lateral pullout (Burial depth of 30 cm). The predicted response using ASCE (1984) equations for buried pipelines is also shown.

The predicted lateral response for the cable using ASCE (1984) equations for buried pipelines is also shown in the same figure. It is of interest to note that the general trend of the predicted response is in reasonable agreement with the experimental observations although the peak lateral force is under-predicted by the ASCE (1984) equations. It is important to note that the equation used in the predictions has been developed for a 2-dimensional plane-strain movement whereas the lateral pullout test simulated in the chamber in fact is a three dimensional cable-soil interaction problem; as such, it is not surprising that the observed lateral resistance is larger than that derived from the analytical approach.

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4. Conclusion

A full-scale laboratory testing program was undertaken using a large soil chamber to examine the response of buried power transmission cables subject to permanent relative ground displacements. A series of tests were conducted where buried cables were subjected to longitudinal and transverse pullout loading. The test results have been compared with the predictions from the ASCE (1984) guidelines for assessing the performance of buried pipelines under relative ground movements.

The peak soil loads under relative axial soil movements on cables buried in dense soil were noted to be under-predicted by the current approaches used for buried pipeline design; this is likely due to the increased soil normal stresses on the cable due to constrained soil dilation not accounted by the current approaches. It appears that the limitations in the current approaches for the estimation of axial soil loads on steel pipes in dense soils may also exist for the cables buried in dense soils. In using the ASCE (1984) approach, the determination of the lateral earth pressure coefficient (K) that adequately represents the normal soil pressure on the cable seem to present a challenge.

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