Thermo-mechanical behavior of cables installed in vertical shaft

Jicable'15, : 21-25 June 2015 - Versailles – France

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22 June 2015

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Agenda

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   - Test and verification of cleat design
   - Test on vertically installed cables
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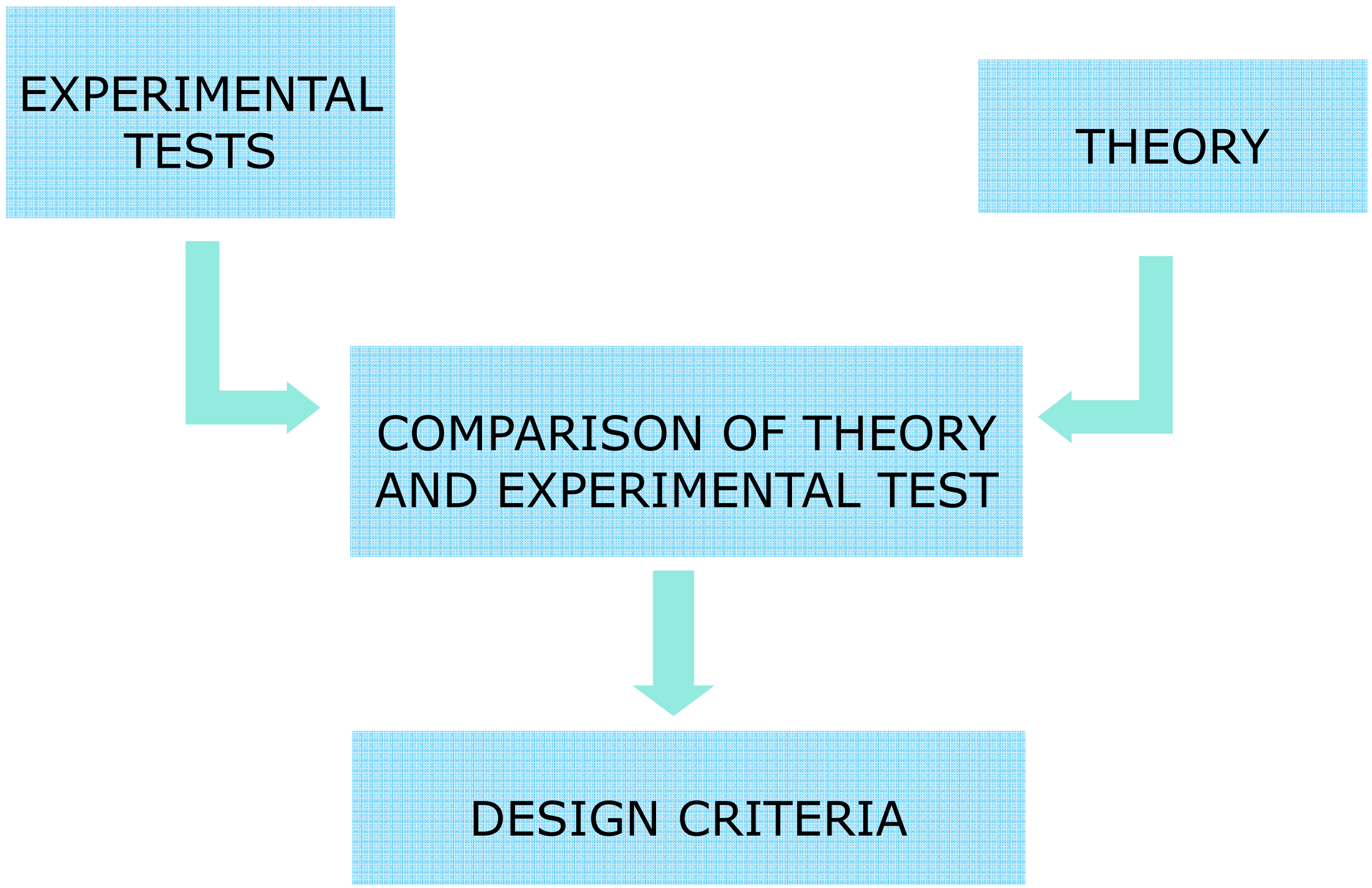
Introduction

- There is experience with cable installation in shaft with different types of cable (OF, XLPE).
- Generally small conductor cross section and reduced temperature variation during thermal cycles.
- The majority of cable installation in deep shaft is with rigid straight installation.
- Design criteria must be revised and adapted to more demanding conditions: large power capacity systems.

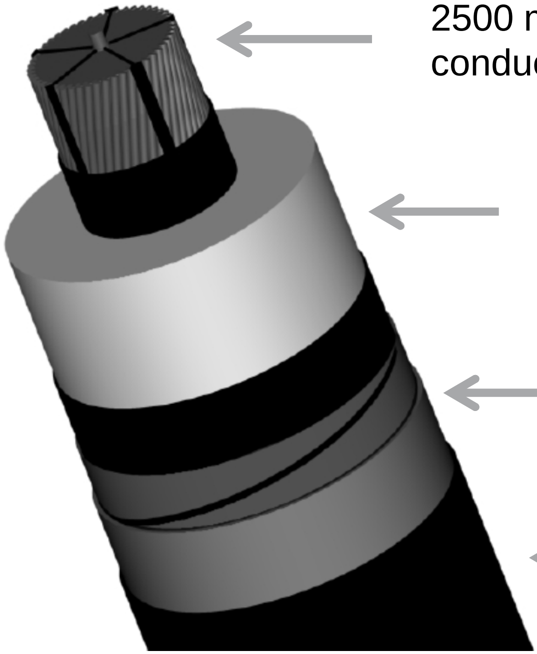
Introduction

RESEARCH PROGRAM



EXPERIMENTAL SET UP AND TESTS

CABLE DATA



2500 mm^2 Aluminum conductor

XLPE Insulation

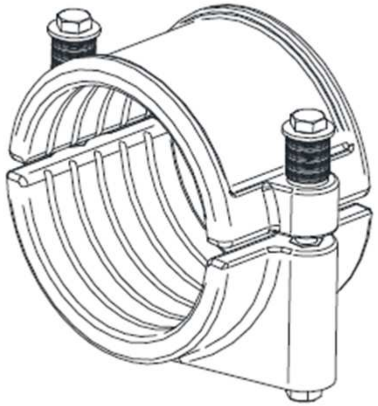
Aluminum sheath

PE outer sheath

EXPERIMENTAL SET UP AND TESTS

TEST AND VERIFICATION OF CLEAT DESIGN

- Cable cleats with spring loading arrangement.
- Spring package designed on purpose to:
  - compensate for the cable expansion and contraction
  - to provide the necessary clamping force.

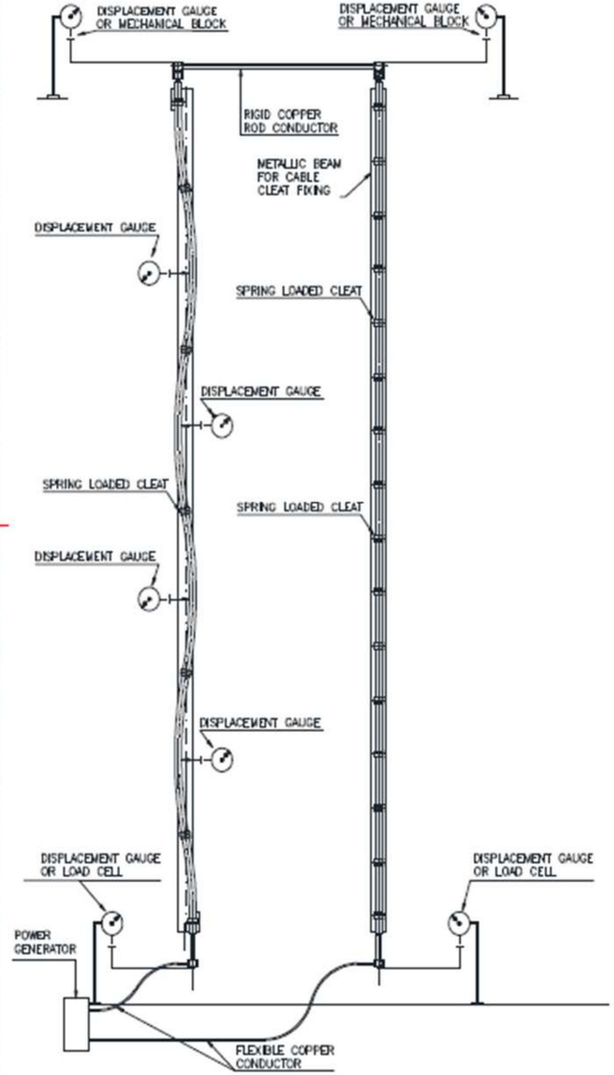


- Check cable deformation at clamp position
- Check clamping force with constant load and temperature

EXPERIMENTAL SET UP AND TESTS

TEST ON VERTICALLY INSTALLED CABLES – TEST SET UP

- Two cable sections have been installed and vertically fixed with clamps on a metallic structure.
- One cable section has been installed in a straight rigid configuration.
- A second cable section has been installed in a flexible snaked configuration.



EXPERIMENTAL SET UP AND TESTS

TEST ON VERTICALLY INSTALLED CABLES – MEASUREMENTS

Displacement gauges and load cells have been installed to measure the following parameters:

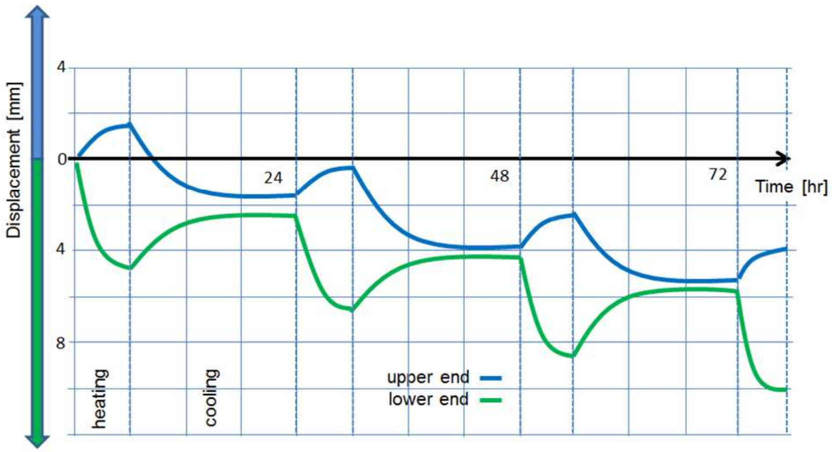
- Vertical displacement of the cable with respect to cable cleats,
- Lateral displacement of the sags for the cable in snaking configuration,
- Displacement of the cable components.
- Thrust forces generated during load cycles

EXPERIMENTAL SET UP AND TESTS

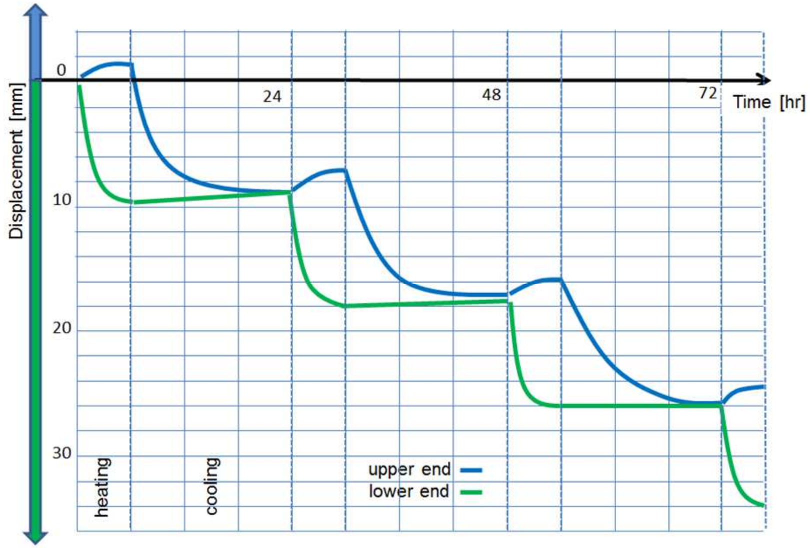
TEST ON VERTICALLY INSTALLED CABLES – LOAD CYCLES

The cable samples have been subjected to repetitive load cycling by circulating current in the conductor.

- Test 1 - Both cables tested with both upper and lower ends rigidly fixed.
- Test 2 – Both cables tested with upper end rigidly fixed and lower end free to move.
- Test 3 – Both cables tested with both ends free to move



Test 3 - Conductor displacement – Flexible/snaked



Test 3 - Conductor displacement – Rigid/Straight

EXPERIMENTAL SET UP AND TESTS

TEST ON VERTICALLY INSTALLED CABLES
MAIN RESULTS AND CONSIDERATIONS

- The test results are in line with the expectations based on previous tests, practical experience and current available calculation formula (e.g. CIGRE' TB 194).
- The thrust generated by a cable in rigid configuration is approximately one order of magnitude greater than in flexible installation.
- The displacement of the conductor of the cable versus outer components of the cable is greater in the cable in straight rigid configuration.
- In the Test 3 configuration it has been noted a general downward movement of the inner core of the cable compared to the outer cable components. This movement is greater in the cable installed in straight rigid configuration.
- No movement of the cable with reference to the cleats position have been noticed both in flexible sagged and in close cleated rigid configuration.

THEORY

The theory has been developed with the following purposes:

- To calculate/quantify the movement of the conductor with respect to the sheath during thermal cycles.
- To provide a design tool applicable to other possible shaft installation arrangements

THEORY

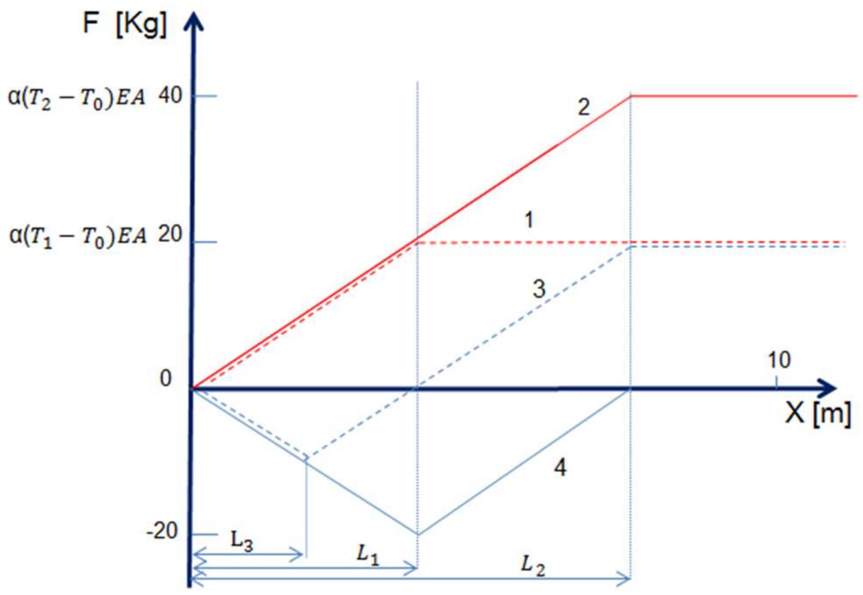
THEORY - HORIZONTAL INSTALLATION

Main assumptions – Simple case:

- The cable is long enough to avoid any interaction between the two extremities.
- The cable is horizontal.
- The cable is rigidly fixed.
- The cable core is free to move at the extremities of the cable.
- Relative movement between different cable components generate a friction force per meter.
- Before being energized the cable is at ambient temperature and the conductor has no tensile or compression stresses.

THEORY

HORIZONTAL INSTALLATION – 1st Thermal cycle



- Thermal cycle is presented as a sequence of four steps.
- Axial force at the extremity is equal to zero.
- At a sufficient distance from cable end no axial deformation of the conductor is possible.

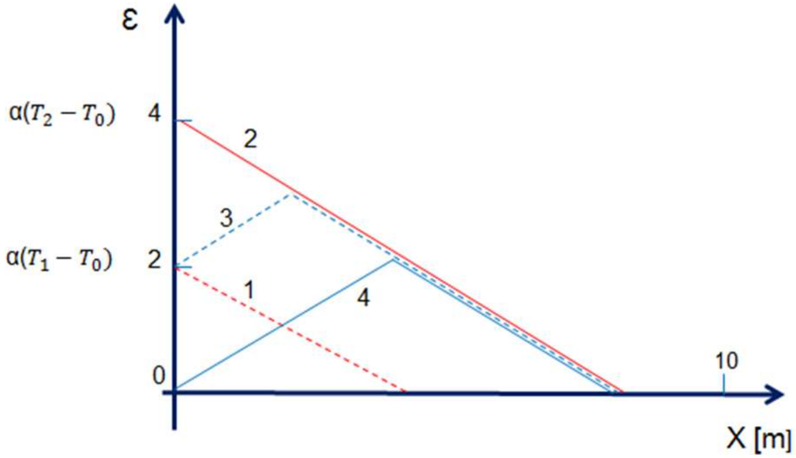
$F(x) = f \cdot x$ Compression force

$F_{max} = f \cdot L_1 = \alpha \cdot (T_1 - T_0) \cdot EA$

$L_1 = \alpha \cdot (T_1 - T_0)\dfrac{EA}{f}$ Cable section with movement

THEORY

HORIZONTAL INSTALLATION – 1st Thermal cycle



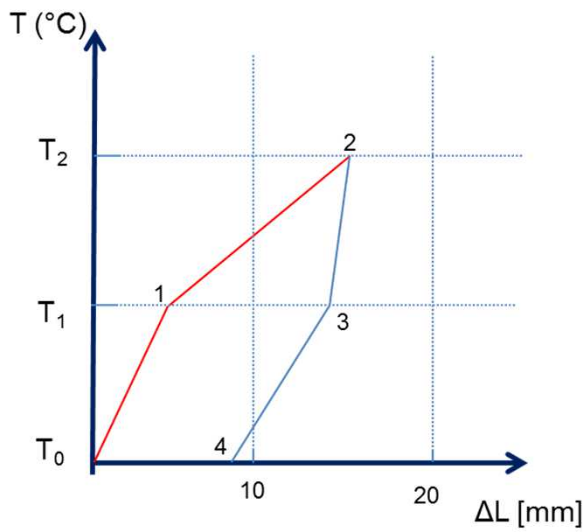
$$\varepsilon(x) = \alpha \cdot (T_1 - T_0) - \frac{F(x)}{EA} = \alpha \cdot (T_1 - T_0) - \frac{f \cdot x}{EA}$$ Elongation

THEORY

HORIZONTAL INSTALLATION – 1st Thermal cycle

$$\Delta L(x) = \int_{x}^{L_1} \varepsilon(x) \cdot dx$$

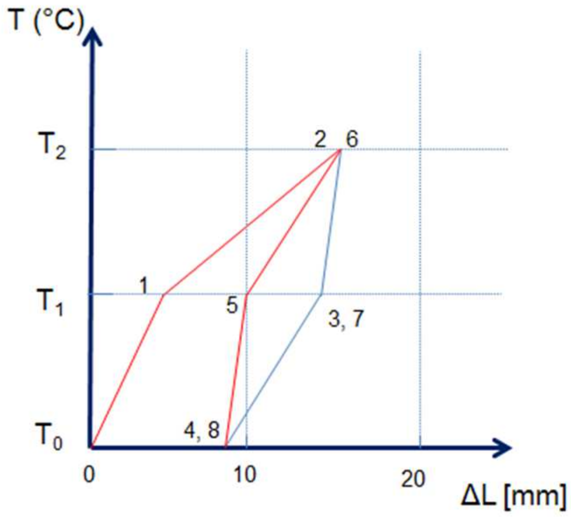
Displacement of the conductor is calculated by integrating



After the complete thermal cycle the conductor does not return to its original position.

THEORY

HORIZONTAL INSTALLATION – 2nd Thermal cycle

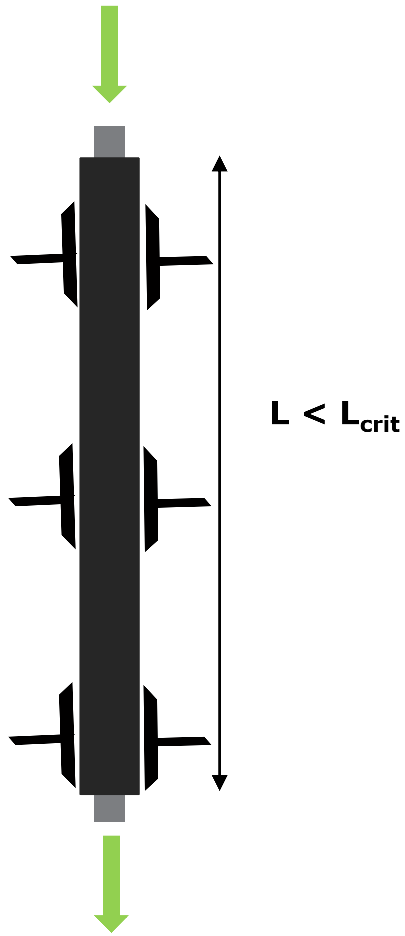


- The displacement after any complete cycle is the same as after the first one.
- The situation at the maximum temperature is exactly the same independently of any previous type or number of thermal cycling.
- With reference to the example it can be easily understood that if the total length of the cable were less than $2L_2$ there would be an interaction between the two extremities.
- As a practical consequence the maximum axial force and the maximum displacement would be less than previously calculated and the displacement at both extremities is the same for symmetry reasons.

THEORY

VERTICAL INSTALLATION

- The weight must be added or subtracted to slipping force in case of upward or downward movement respectively.
- No interaction between the top and bottom extremity if the cable is long enough.
- The displacement at the top after the load cycle is smaller than at the bottom.
- At a sufficient distance from the extremities there is no downward movement of the conductor.
- If the length of the cable is reduced to less than a critical value there is a displacement of the entire conductor at any thermal cycle



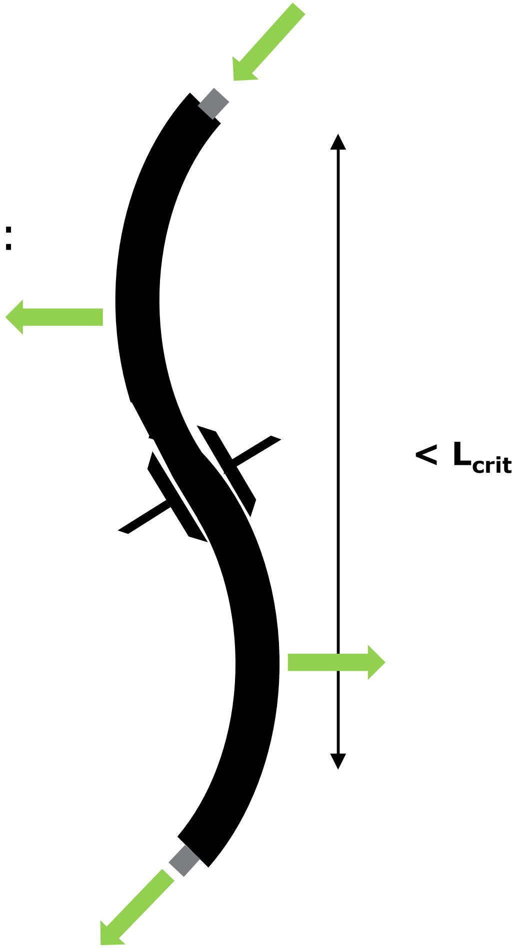
THEORY

SNAKED/FLEXIBLE INSTALLATION

Similar calculations can be done for flexible/snaked installation but appropriate adjustments are necessary.

Two main phenomena should be considered:

- The cable has a certain geometrical deformation and elongation between the fixing cleats.
- The slipping force of the conductor is increased by the snaked configuration.



Improved behavior with respect to the displacement of the conductor

DESIGN CRITERIA

- Experimental tests are in agreement with the theory applied to the test installation arrangement.
- At any load cycle we observe an outward (upward) displacement at the upper extremity in the heating phase followed by a larger inward (downward) displacement in the cooling phase.
- At the lower extremity the outward (downward) displacement is larger than the inward (upward) displacement.
- The phenomenon is qualitatively the same for rigid and flexible cable, but the situation is clearly much more favorable in the flexible installation.

DESIGN CRITERIA

- The experimental tests validate the theory
- The experimental tests give quantitative information on the behavior of the real cable installed rigid or flexible under load cycles.

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DESIGN CRITERIA

- Study of the cable in real situations in a vertical shaft having the physical parameters under control.
- Calculation for a given height of the shaft what would be the maximum service temperature to avoid the risk of downward slippage of the conductor or vice versa what would the critical length for a given maximum temperature.
- Conservative approach with cable ends free to move. The mechanical reaction is present at the ends (bends, terminations etc.) of the shaft reducing the movement of the conductor.
- Good design practice is to minimize the movement of the conductor at the ends.


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