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Tohoku Electric Power Network Co., Inc.
FURUKAWA ELECTRIC
FITEC

Study Committee B1

Insulated Cables

10689_2022

Development of Analytical Method for Power Cable Creepage Phenomenon in Duct

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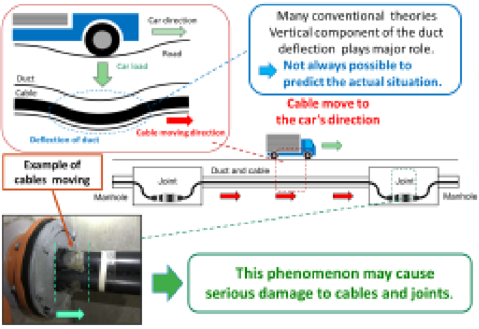
1. The probrem of CABLE CREEPAGE PHENOMENON

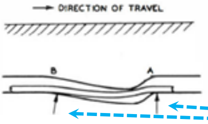
Cable Creepage Behavior

→ The cable in the duct moves toward the direction the car goes.



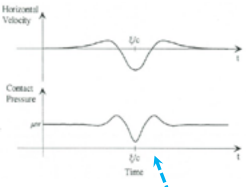
2. The conventional theories

(1) A.C.Timmis "Surf-riding theory"



Caused by unequal vertical deflection in the duct during car passage.
⇒ No reason for the unequal duct deflection was explained.

(2) J.K.Kim, J.S.Yi

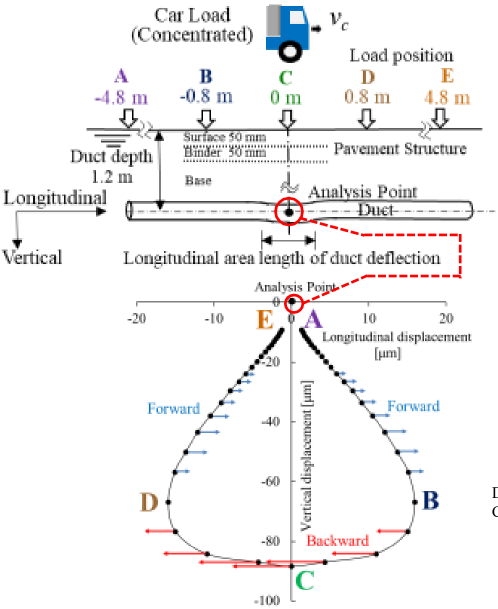


When a car is passing longitudinal slip velocities (car direction and opposite direction) occur between the duct and the cable.

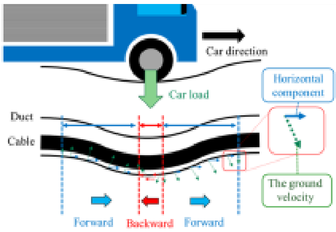
In the backward area, the vertical deflection of the duct causes the contact pressure (frictional force) decrease and the cable moves forward. **⇒Under Japanese equipment conditions, the decrease in contact pressure is not regarded as a major factor (Our FEM analysis results)**

3. The new theory of CABLE CREEPAGE PHENOMENON

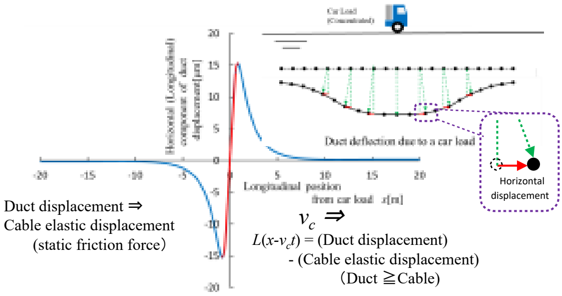
The new theory focus on the horizontal (longitudinal) component of frictional force



Ground(Duct) displacement for each car load position (FEM analysis).



The Ground Movements Caused by a Car Load



Longitudinal component of ground (duct) displacement.
(Load is above the origin.⇒Radial displacement around the origin)

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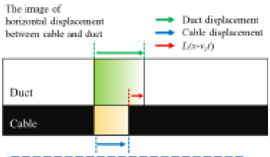
4. The new theory‘s mechanism to move a cable in car direction

Amonton–Coulomb law of friction ; Dynamic friction force is independent of the sliding speed.

⇒ The value of dynamic friction force is regarded as a constant.



Step of drawing graphs

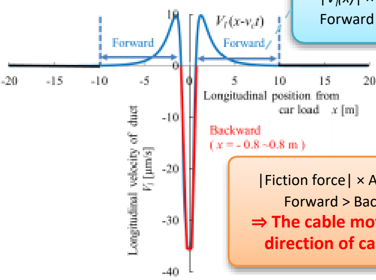
1. $L\ (x\text{-}V_ct)$ = (Duct displacement) – (Cable elastic displacement)

↓ Time derivative

2. Longitudinal sliding velocity

↓ **Amonton-Coulomb law**

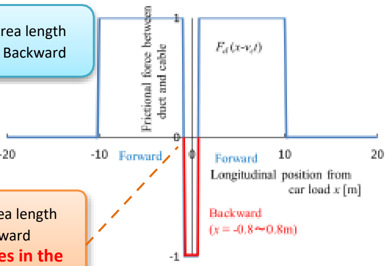
3. **Dynamic frictional force**



|$V_l(x)$| × Area length
Forward = Backward

|Fiction force| × Area length
Forward > Backward
⇒ The cable moves in the direction of car travel.

Longitudinal sliding velocity V_l between duct and cable



Dynamic frictional force F_d between duct and cable.

5. Development of the cable creepage analysis system

$$[k]\ \vec{U} + [m]\ \vec{a} = \vec{F} + \vec{F_f}$$

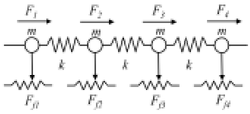
$\vec{F}$; Cable creepage force vector (cable internal stress) [N],

$\vec{U}$; Displacement of a mass point vector (elastic displacement of cable) [m],

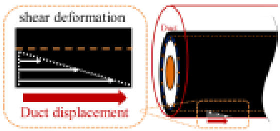
$\vec{a}$; Acceleration of mass points vector [m/s²],

[k] ; Stiffness matrix, [m] represents the cable mass matrix [N],

$\vec{F_f}$; Dynamic frictional force vector between the duct and cable [N]



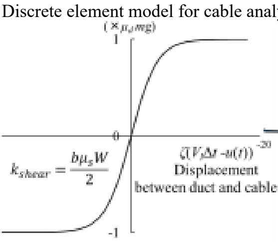
Discrete element model for cable analysis.



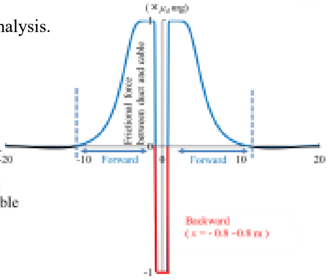
Amonton–Coulomb law of friction

$$F_f = -\left(\frac{2}{1+e^{b(v_l\Delta t - u(t))}} - 1\right)\mu_d mg$$

- Shape factor b incorporates the cable sheath shear deformation.
- Sigmoidal function can stabilize the numerical calculation because it is a differentiable function



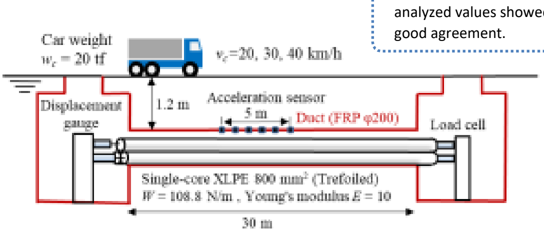
$$k_{shear} = \frac{b\mu_s W}{2}$$



Dynamic frictional force F_d between duct and cable.(Analysis)

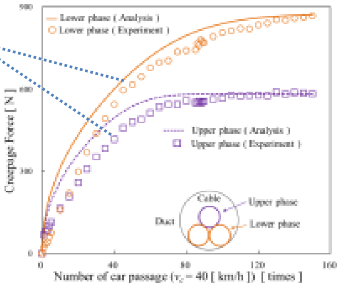
6. FULL-SCALE EXPERIMENT

The measured and analyzed values showed good agreement.



Duct deflection(Measured values), Vertical displacement: 90–140 μm
Longitudinal area length of the deflection:7–11 m

Overview of the full-scale experiment.



Experimental and analytical values of cable creepage force.

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7. Discussion—Condition of cable creepage occurrence

The cable creepage was analyzed for different conditions under general facility conditions in Japan.

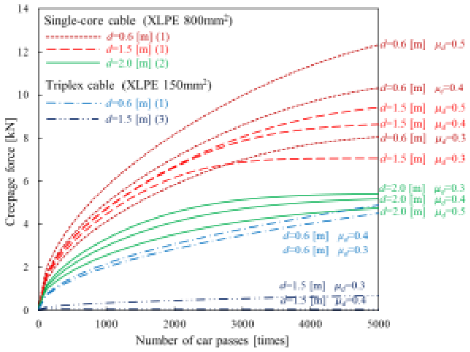
Table . Analysis conditions for ducts and cars

Duct burial depth *d*	m	0.6	1.5	2.0
Car weight w_c	tf/m	8.57	20	27.17
Longitudinal area length of duct deflection	m	≒4	≒10	≒20

To keep the value, w_c is set heavier as duct burial depth *d* is deeper

⇒ The action makes longitudinal area length longer.

The maximum longitudinal displacement of the duct ; ***35.7 μm***



Variation of the maximum cable creepage force with the number of car passes.

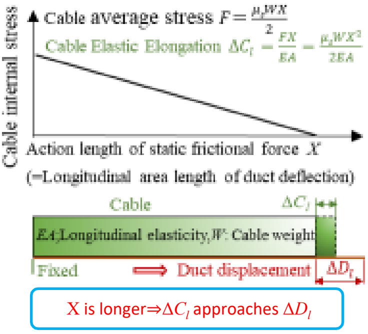
Table . Analysis conditions for cables

		Single-core 800 mm²	Triplex 150 mm²
Weight	N/m	108.8	112.7
Longitudinal elasticity $EA \times 10^6$	N	8.01	1.47
Dynamic friction coefficient μ_d		0.3, 0.4, 0.5	0.3, 0.4

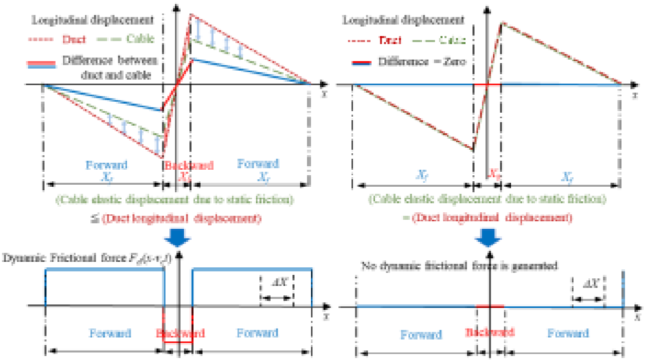
The cable length is 300m

Table . Occurrence conditions of cable creepage

Equipment conditions	(1) Single-core d = 0.6, 1.5 m	(2) Single-core d = 2.0 m	(3) Triplex d = 1.5 m
Creepage force	Increase at μ_d increase	Decrease at μ_d increase	Almost zero at μ_d = 0.4
Length of ΔC_l and ΔD_l	Both forward and backward area : $\Delta C_l < \Delta D_l$	forward area : $\Delta C_l \approx \Delta D$ backward area : $\Delta C_l < \Delta D$	Both forward and backward area : $\Delta C_l \approx \Delta D_l$



Elastic displacement of cable when friction force is applied



Schematic diagram of frictional force acting on the cable.

8. Conclusion

The cable creepage results from the horizontal (longitudinal) component of duct deflection caused by the car load.

1. **As a car moves over the duct, local longitudinal sliding velocities are generated between the duct and cable.** These sliding velocities consist of a forward area in the direction of the car's motion and a backward area in the opposite direction.
2. **The Amonton–Coulomb friction law states that the dynamic friction force is independent of the sliding speed**. Applying this law to the sliding velocities, the amount of dynamic friction force acting on the cable is greater in the forward area than in the backward area, **This difference in the dynamic friction force amounts causes the cable to move in the forward direction.**
3. **Based on this theory, we developed a cable creepage analysis system that is readily useful on an ordinary PC.** Furthermore, the theory validity was verified by conducting a full-scale experiment and by confirming that the measured and analyzed values showed good agreement.