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A Preliminary Study on the Long-Term Structural Stability of Ventilation Ducts in Cold Regions

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Abstract

The construction of roadways in permafrost regions modifies ground-surface conditions and consequently, negatively varies thermal stability of the underlying frozen soils. To avoid the thawing of the permafrost layer under the scenario of global warming, roadways are usually laid on a built-up embankment, which not only disperses the traffic loads to underlying layers but also minimize the thermal disturbance. In the embankment, duct ventilation, or called air duct, can be embedded to further cool the underlying permafrost. While the thermal performance of duct ventilations has been well documented, the long-term structural stability of duct ventilation remains unknown. This study examines the structural stress of ventilation ducts that are placed in harsh weather such as the Qinghai-Tibet Plateau. The ducts are currently buried in the embankment filler, with the wind-outlet and -inlet ends exposed and cantilevered out of the embankment. Field studies found that the exposed parts have plagued cracking and even failures, especially at the fixed end of the cantilevered part. Damages of these concrete ducts are attributed to cyclic freezing-thawing attack, thermally-induced stresses, moisture-induced stresses, and concrete swelling. These physical attacks are caused by the harsh weather in the Qinghai-Tibet plateau. It is recommended to insulate the exposed part of the ducts and to fabricate durable and dense concrete ducts.

Keywords: Concrete; Freezing-Thawing; Thermal Stress; Swelling and Shrinkage; Cracking.

1. Introduction

Air ducts have been applied to cool foundations built in cold regions since 1970s [1-6]. The air ducts are placed parallel to the embankment shoulder (Figure 1-b) to counteract the wintertime insulating effects of the snow cover and to cool the underlying permafrost soils through natural convection inside the ducts. In the last decade, ventilation duct has been applied to cool roadbeds built in cold regions, such as the Qinghai-Tibet Railway (Figure 1) [1-3]. Differently, ducts in the roadbeds of Qinghai-Tibet Railway are a row of concrete pipes inserting through an embankment, with wind-inlet and -outlet parts extending and overhanging out of roadbeds (Figure 1). The duct performs cooling effects because it allows airflow to deposit cold energy in the duct in cold seasons [7]. Although air inflow into the duct also leads to the heat intake in the duct, in the Qinghai-Tibet plateau the duct tends to introduce a negative heat budget to the ground due to the windy weather in winter but the clam weather in summer. To diminish heat intake, temperature-controlled shutters may be installed in wind inlet and outlet to prevent air inflow during summertime [8, 9]. The cooling effect can be further enhanced if the duct is perforated to allow the air contacting directly with the soil and to allow turbulence air flow along the inner ring of the ducts.

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The performance of the air ducts have been reviewed by Qin and zhang [10]. Duct-ventilated embankments have been widely reported as powerful foundation to cool the permafrost in the sub-grade [11-13]. Both numerical studies and field observations report that duct-ventilated roadbeds may experience 0.5-2.0 ºC lower than traditional earthen roadbeds (without the protection of the ducts). The intensity of the cooling effect depends on the embankment geometry, the local weather, and to a greater extent, on the setup of the ducts [8, 14]. The air ducts are also installed in combination with air roadbed-cooling techniques such as crushed rock layer [7, 15]. So far, numerical studies and field observations, as well as some associated heat-transfer theoretical analysis, are stood on an uncorroborated assumption that the ducts would structurally sustain during their expected lifetime (50 years) [16]. Although in the last decade, there are extensive studies on the techniques of keeping roadbeds in permafrost regions by reducing the solar absorption [17-19], enhancing the air convection [20, 21], and their combinations [22, 23], the long-term structural stability of air ventilation ducts remains unknown and has not been reported yet. As most of ventilation ducts are of concrete texture, it is questionable whether the ducts remain structurally intact during their lifetime.

This paper therefore focuses on the long-term structural stability of ventilation ducts in cold regions. The duct's structural stability in current stage is reported from a field investigation. Structural damages of in-service ducts are examined from perspective of physical attacks. Potential attacks consist of freezing-thawing attacks, thermal-induced stresses, and moisture-induced stresses. It is recommended to cast durable concrete ducts against potential damages and to prevent cantilevered parts of the ducts being exposed to harsh environment.

Figure 1. Ventilation ducts, seen as a row of concrete pipes in the earthen dam, are embedded in a railroad embankment to cool the underlying permafrost in Qinghai-Tibet Railway. Air enters from one end (inlet) and leaves from the other end (outlet)

2. Field Investigations

A field trip was conducted to closely inspect the structural stability of ventilation ducts that were embedded in the embankment section DK1141 in the Beiluhe Permafrost Station (N34.82, E92.92) (Figure 2). In this section the ventilation ducts were embedded about 3.0 m above the natural ground surface and approximately 2.5 m beneath the railway surface (Figure 3). The duct consisted of reinforced concrete, having an internal dimension of 40.0±0.1 cm and a wall thickness of 3.5±0.1 cm (Figures 3e and 3f). The overhung, exposed parts of the ducts were 1.0-1.2 m.

The exposed parts had plagued structural distresses and even failures. Cracking's appeared both in the inner and outer rings of the ducts, with a principal cracking propagation not necessarily at axial or circumferential directions (Figures 3c and 3d). Cracking in the inner wall of the duct appeared primarily at the exposed part but seldom showed at the buried part (Figure 3d). In several cases with serious distresses, some ducts were already collapsed, especially at the fixed ends of the cantilevered part (Figure 3e). Some failure exposed parts of the ducts overhung at the embankment or even rolled to the embankment toe (Figures 3a and 3b). Coarse aggregates used in the reinforced duct wall were quarried riverbed aggregates (Figure 3f). At the failure profile, the aggregates surface was intact rather than fragmented. There were some white mottles at the inner surface of the distressed ducts (Figure 3e). Some chemical compounds had been leached and deposited at the inner of the duct.

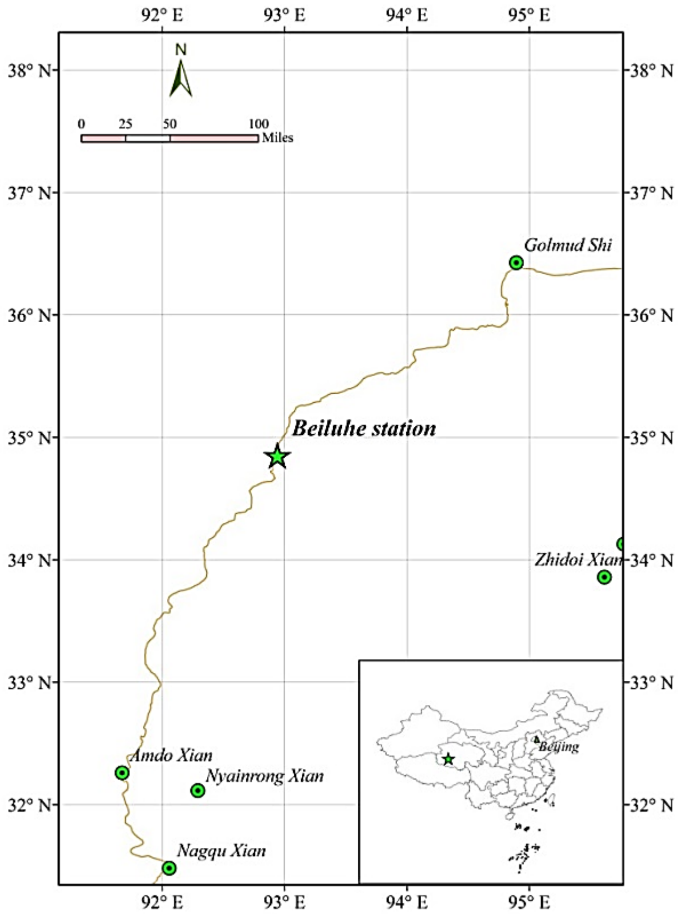

Figure 2. The study site is at the Beiluhe permafrost station (N34.82, E92.92)

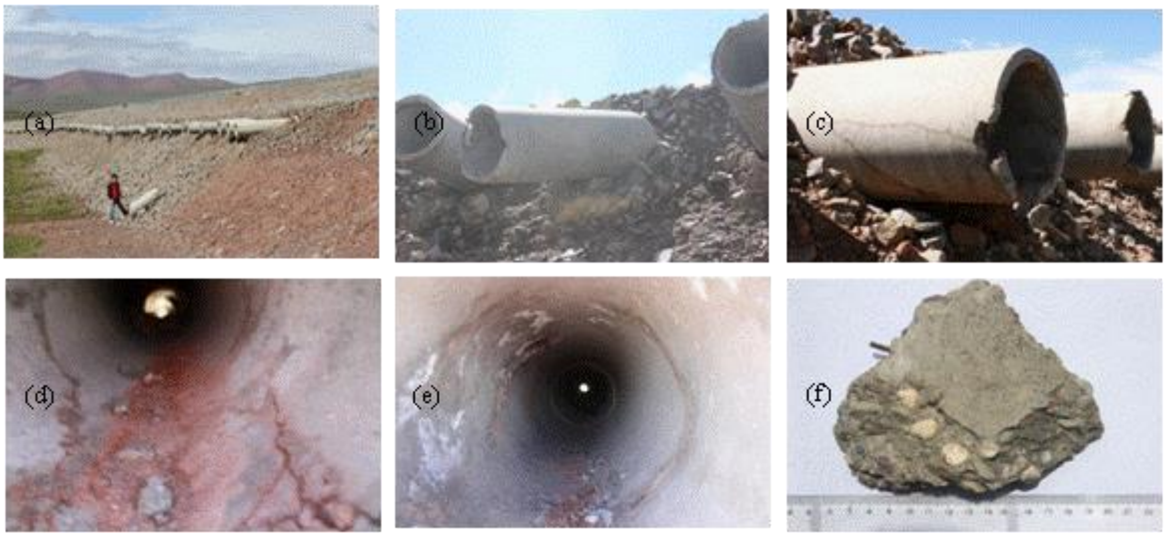

Figure 3. Distresses and failure of ventilation duct at DK1141 section at Beiluhe site

3. Ventilation-duct Damages and Possible Solutions

Ventilation ducts are prone to damages due to their structures. Its thin wall and its relatively-large specific area allow cyclic heat and moisture penetrating easily. As the ducts are served at harsh cold climate, the related damages at least can come from freezing/thawing attack, thermal stress distortion and wetting/drying damage.

3.1. Freezing-thawing Attacks

Ventilation ducts in cold regions are especially susceptive to freezing and thawing attacks because the duct is of concrete-ring structure with a thin wall ranging from 4.0-6.0 cm. Thermal penetration through this thin wall requires

20~60 min only, provided a normal concrete with a thermal diffusivity of 1.06×10^{-6} m^2/s [24]. A duct possibly suffers from a cycle of freezing-thawing during one day because the daily air temperature on the Qinghai-Tibet plateau varies from negative to positive, or vice versa. The exposed part of an individual duct so far has already been weathered approximately 5000 freezing-cycles, considering that the Qinghai-Tibet railway has serviced for approximately 14 years (2004-2018). Under these harsh conditions, it is not surprised that some of in-service ducts have been cracked and even failed, although they are reinforced.

The long-term structural stability of the ducts looks pessimistic. The exposed part of a specific duct will be expected to weather approximately 20000 freezing-thawing cycles when 50-year lifetime of the railway is projected (to 2054). The freezing-thawing attacks may proceed nonlinearly, leading to worse damages because once the duct cracks, external heat penetrates through the ducts wall in a faster, more exhaustive manner. Suffered from these serious attacks, no concrete structure can further sustain even if the structure is reinforced and even if the concrete duct has been air entrained to enhance the freeze-thaw resistance.

3.2. Thermally-induced Stress

The ducts are suffered from thermally-induced stresses. The Qinghai-Tibet plateau has distinct daily temperature amplitude. The duct and its wall thus experience different temperature in different portions. Differential temperature profile through a concrete structure develops internal stress because potential deformations through the duct wall are resisted by the compatibility of internal elements, by the structure of the duct, and by the external forces. The stress magnitude depends on their mechanical properties and on the geometry of the ventilation ducts (Figure 4).

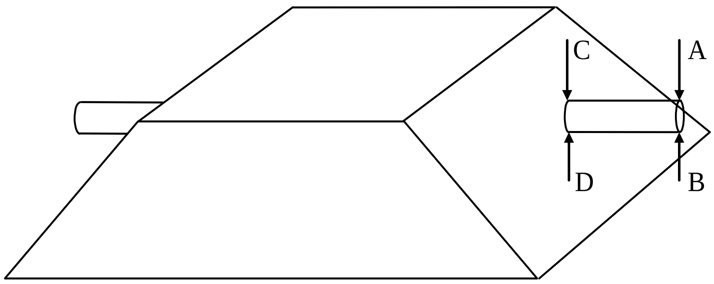

Figure 4. A schematic show for a duct-ventilated embankment. A-upper free end; B-lower free end; C-upper fixed end; D-lower fixed end

Thermally-induced stresses attack the upper fixed end of the exposed, cantilevered part (Figure 2) in most pronounced manner. During the daytime, solar radiation heats up the upper side of the exposed part whereas the lower side remains relatively cold [19]. Different temperature through a concrete structure leads to different deformation potentials, resulting in the cantilevered part being downward bent. This deformation potential is resisted by the pipe structure of the cantilever. It thus develops compressive stresses at the upper fixed end and tensile stress at the lower fixed end. The magnitude of the stress developed depends on the temperature gradients as well as the wall's mechanical properties (e.g., Young's modulus and Poisson ratio). These stresses developed during the daytime are reversed when the upper side of the exposed part cools faster than the lower (σ_c: Figure 5). In addition, the upper side of the fixed end also suffers from the tensile stresses resulting from the self-weight by the cantilevered part. Combination of these stresses may crack the upper side of the fixed end.

The preceding paragraph mentions only the stress developed in the axis of the cantilevered, exposed part. This part is also suffered from circumferential shear stress. Compared to the exposed ends, the buried part is surrounded by the soil and thus experiences relatively-stable temperature variation. The buried part tends to deform less; but the exposed part may expand or shrink circumferentially in a daily cycle. This differential deformation along the duct's axial must be compatible in the joint zone (the clamped end of exposed part) between buried and exposed parts. The compatibility along the axial develops shear stress at the clamped end of the cantilever part (τ: Figure 5).

At the circumferential direction, normal stresses also develop through the wall of the duct. When the ambient thermal conditions (solar radiation, wind, air temperature) vary, the outer ring of the duct wall responses faster than the inter ring so that differential temperature profile develops through the duct wall. When the outer ring is colder, it suffers from tensile stress but the inner ring, compressive stress. A reverse temperature cycle would develop tensile stress (σc = Figure 5)). The magnitudes of the stress depend on the mechanical properties of the wall, the duct geometry, and to a great extent on the shape of the temperature profile. These circumferentially thermally-induced stresses have reverse signs when the outer ring is warmer. The stress profile through the duct wall is nonlinear because the temperature profile is nonlinear, with greater stress gradient occurring at the outer wall.

Bent stresses, circumferential shear stresses, and circumferential normal stresses thus simultaneously torture the exposed part of a specific duct, especially its fixed end. All of these stresses repeatedly vary from compression to tension.

Repeated variation of these tri-axial thermal stresses may lead to damage or even cracking developed in the exposed part because concrete structure is brittle material and is susceptive to fatigue damage (Figure 3e). Skew propagations of the cracking (Figure 3c and 3d) is attributed, in part, to that the ducts are experiencing the tri-axial thermal stresses state.

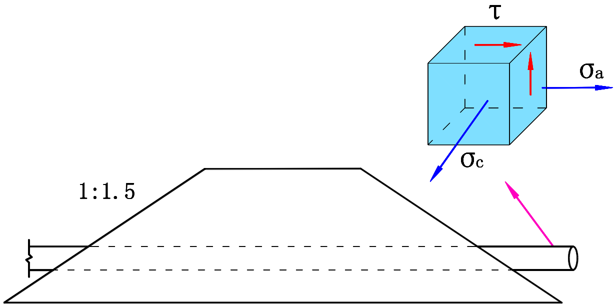

Figure 5. Thermal induced stress at the fixed end of the exposed part of a concrete duct. σ_a= thermal stress parallel to the axial of the duct; σ_c= thermal stress at the circumferential of the duct; τ= the shear stress caused differential expansion/shrinkage between the buried and exposed parts of the duct

3.3. Wetting-drying Induced Stress

Cyclic wetting and drying is other influential factor that substantially damages the thin duct wall. Repeated wetting and drying develops differential moisture profile through the wall. Some portions of the exposed part have relatively-stable moisture content while other portions experience varying moisture content. The portion with high moisture tends to swell, whereas others having less moisture tend to shrink. The associated swelling and shrinkage can develop moisture-induced stress profile through the duct in the same way as thermally-induced stress profile. That is, the moisture-induced stresses contribute another tri-axial stress state to the exposed part of the duct.

Compared with the thermally-induced stresses, moisture-induced stresses vary in lower frequency. Cyclic wetting and drying occurs at a long (weeks or even months) and unpredictable period. During the early stage of a long drying spell, near-surface moisture of the exposed part begins depleted whereas the interior concrete wall has relatively higher relative humidity. Differential moisture profiles are thus developed, depending on the thickness of the duct. For the 4-6 cm thickness of the duct wall, the drying font penetrating through the wall requires approximately 20-50 days, provided the moisture diffusivity of concrete is 1.6×10^{-6} m^2/h (the moisture diffusion within concrete is highly nonlinear and more complicate). This suggests that in the Qinghai-Tibet plateau, the whole exposed wall is moisture-depleted during the later stage of the drying wintertime because the local drying spell lasts from normally from October to March [25]. The moisture of the wall duct is depleted to a degree approximately equal to the local air relative humidity, which is about 50% during wintertime [26]. Therefore, tensile stresses develop in the near-surface of the duct wall whereas the interior wall suffers from compressive stress. Signs of these stresses do not vary during the whole drying spell because the moisture of the wall is not replenished until next wetting period. In this long drying spell, the moisture diffusion occurs in a very slow manner; magnitudes of these stresses thus vary slowly.

4. Solutions to Improve the Performance of Ventilation Ducts

Damages of ducts in the Qinghai-Tibet railway embankment are different from damages of duct used in Northern America, where an air duct is placed parallel to the embankment side slope [4]. Typically, an air duct have a length of 30-50m and a diameter of 20-70 cm, with the inlet and outlet at the same side slope of the embankment [27]. In this configuration, the duct does not need to sustain traffic loadings, so the ducts are commonly PVC pipes. The inlet is a pipe buried close to the bottom of the embankment, and the outlet is set at a higher elevation to form a chimney effect. As the air ducts are not straight line, the airflow in the duct can be blocked due to internal water ponding and ice formation. Such problems are free for the ducts in the embankments of the Qinghai-Tibet Railway due to the local arid climate. However, as main part of the duct is buried under the side slope and with very few portions of the ducts expose, air ducts in Northern America are free from thermal stresses.

As has been highlighted, the long-term stability of the duct is being threatened by physical attacks due to the local harsh climate. It does not mean that the duct cannot be fixed. It does mean that it is urgent to find practical solution to fabricate a duct that is sustainable sufficiently to resist the physical attacks. These attacks can be alleviated if the ventilation ducts are durable concrete and if the exposed parts are insulated from the harsh weather.

4.1. Fabricating Durable Concrete Ducts

Durable concrete ducts may help increase the freezing-thawing resistance of the ducts. Cold weather concreting usually mandates an acceleration of the cement hydration. In this weather, fast heat generating within the hydrating concrete introduces micro-cracking so that a durable concrete is seldom achieved. The ducts are therefore always precast concrete. The precast ducts are expected to be added mineral admixtures (fly ash, ground-granulated blast furnace slag, or silica fume) to allow the cement hydrating slowly and to develop stress progressively. The pozzolanic reaction reduces the heat generation during initial hydration state and thus promotes a more ordered, more crystallized hydration structure. More dense, ordered hydration matrix is also expected because pozzolanic reaction converts the hydrate calcium hydroxide to calcium silicate hydrate (CaH_2SiO_4) [24].

When these pozzolanic admixtures are used properly, the fabricated concrete has long-term compressive and tensile stresses that are one-and-half greater than normal Portland cement concrete [24]. The fabricated ducts in this case, if air-entrained appropriately, are expected to resist better to the freezing-thawing attacks. Concrete ducts with pozzolanic reaction also reduce the moisture-induced stresses. This type of concrete is structurally denser than normal Portland cement concrete. It thus has lower moisture diffusivity, better resisting to the moisture incursion and reducing the near-surface swelling and the subsequent swelling-shrinkage stresses.

4.2. Insulating the Exposed End

As the exposed end of the duct is prone to be damaged, an operative measure to protect the duct is to insulate the outer ring of exposed part. This insulation does not compromise the cooling effect of the ducts because only the buried part is designed to thermally exchange between the air and the surrounding soils. Without conceding the cooling effect, this insulation can be successful from perspective of moisture shield and thermal resistance [28]. The insulation reduces the mass exchange between the duct and external moisture. It is thus useful of mitigating the wetting and drying cycles that the outer ring of the duct wall suffers from. Rainfall precipitation can be drained from the insulation surface. Snow precipitation may accumulate temporarily upon the insulation but when melting, will drain in a manner similar to rainfall runoff. Less water is allowed to invade the surface of the duct. Other than the external moisture shield, the internal moisture lose is also blocked. The insulation prevents near-surface moisture being diffused to the drying air. Internal moisture of an insulated duct thus diffuses slower than that in an un-insulated duct, allowing the creep and viscosity of concrete to damp the shrinkage-induced stresses. The risk of moisture-relative attacks thus reduces if the exposed part is insulated.

The insulation can be also used to reduce the level of the thermal attacks, especially if it is of white color. Insulation decreases the heat exchange between the atmosphere and the ducts, mitigating the freezing/thawing cycles that the duct wall suffers from. It also effectively reduces the temperature difference in the wall. The exposed part of the duct thus experiences a lower level of differential thermally-induced stresses. When the insulation is of white texture, it can reflect the solar radiation to the air [19], lessening the heat absorption during the summer time and thus enhancing the cooling effect of the ducts. Therefore, using white geo-textile or organic foam to insulate the outer ring of the duct is expected to effectively lessen the thermally induced stresses through the duct.

The insulation can further lessen the temperature difference between the exposed part and the buried part. If the insulation has a thermal diffusivity equivalent to the diffusivity of the soil around the buried parts, both the buried part and exposed (insulated) part would experience a similar temperature pattern in daily and seasonal scales. In such a way, both parts experience similar patterns of the thermally-induced stresses too. The associated thermally-relative attacks are mitigated in both axial and circumferential directions. The fixed end of the cantilevered and exposed part is not the most vulnerable portion any more. The thickness of the insulation thus has to be designed according to the buried depth, the expected loadings from the passing train and the upper embankment weight, as well as the strength of the duct wall.

4.3. Use Different Setups of the Ventilation Duct

PVC ventilation ducts are deemed as alternatives for ventilation duct. They are commonly used in Northern America. PVC ventilation ducts are expected to perform a cooling effect similar as the concrete duct. However, PVC may compromise the cooling effects of the ducts because its thermal diffusivity is two orders-of-magnitude less than normal concrete diffusivity. To achieve a convection effect similar to the concrete duct, a PVC duct wall has to reduce one order of magnitude according to heat-transfer theory. This means that the thickness of the PVC wall has to reduce to 4-6 mm to achieve an equivalent cooling effect if this thickness is crucial to the cooling effect of the ducts. Such a thin PVC pipe definitely cannot sustain the combined weights from the upper embankment and the passing trains. PVC ducts therefore usually has a thick wall comparative to concrete ducts [29]; their low thermal diffusivities may compromise the cooling effect. In addition, PVC is of organic material. It may have the ageing problem during the later servicing period. It is also unclear whether the use of PVC duct sustains further critical examinations, especially when 50-year lifetime is considered.

Similar to PVC ducts, perforated concrete ducts may have lower structural stability than expectation. For perforated concrete ducts, cold air sinks from perforated holes into the surrounding soil to store cold energy, and warm air beneath the duct may float up through the holes to dissipate warm energy. These processes do not occur when the air inside the duct is warmer than the air beneath the duct. A perforated duct is thus expected a stronger cooling effect, compared to normal ventilation duct [7]. However, from the perspective of concrete durability, a perforated concrete duct would be demolished in a faster way compared to a normal (un-perforated) duct. As perforated concrete ducts allow moisture penetrating in a faster manner, they may experience more profound moisture-related attacks.

5. Conclusion

Ventilation ducts are applied to cool the roadbeds in cold regions because forced convection through the duct dissipates heat from the embankment to the surrounding air. The duct is designed to expose both ends to the ambient air. It is so thin that it allows heat and moisture penetrating in very short time (20-60 min for heat; 20-50 days for moisture). Due to its concrete texture, the ducts especially their exposed parts are susceptive to weather attacks. Field observations confirm that the cantilevered, exposed parts of the ducts have plagued cracking and even failure. Distresses occur primarily at the fixed end of the exposed part.

Distresses of the ducts are attributed to the physical attacks resulting from the internal moisture- and temperature-differences. The thin duct wall is estimated to suffer from 200-400 annual freezing-thawing cycles. A specific duct in the Qinghai-Tibet plateau has been weathered approximately 5000 freezing/thawing cycles so far. Thermally-induced stresses also develop within the exposed parts. The fixed end of the cantilevered part suffers from tri-axial stresses, being the most vulnerable portion. Tri-axial stresses develop from the differential moisture profile through the duct, and from the differential moisture between the exposed and buried parts. Thermal- and moisture-related stresses results in fatigue damage of the ducts. In addition, wetting and drying can also cause damages to the concrete duct.

It is recommended to protect the duct by insulating the outer ring of exposed part. This insulation retards thermal and moisture penetration through the ducts, decreasing the temperature and moisture gradients through the duct wall and diminishing the degree of physical attacks on the duct. It also recommended is to precast the concrete duct with admixtures like fly ash, silica fume, and/or ground-granulated blast furnace slag. These admixtures allow the cement hydration in a slow manner. They promise a denser concrete structure to weather the predictable wetting-drying cycles, thermal-stress damage, and freezing-thawing attacks.

6. Conflicts of Interest

The authors declare no conflict of interest.

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