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Delayed Shear Crack Formation of Shallow RC Box Culverts in Service

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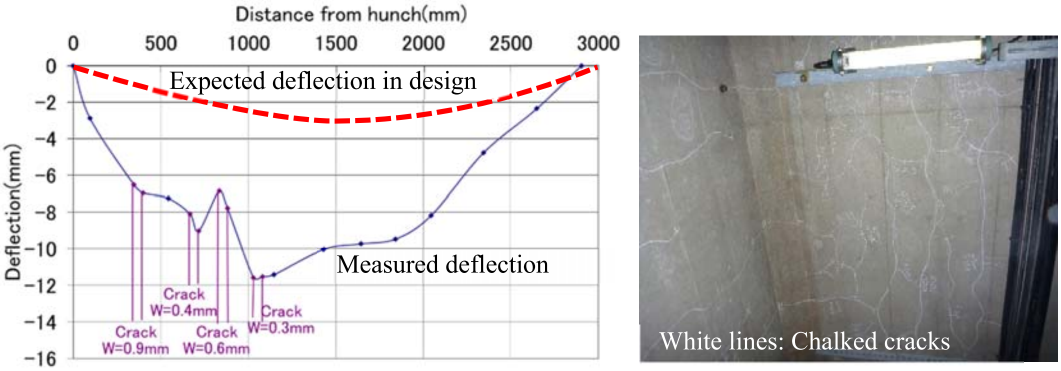
ABSTRACT

Long-term excessive deformation of underground RC box culverts in service was monitored over 20 years and its mechanism is analytically discussed in this study. The long-term excessive deformation possibly attributes to synergy effects accompanying delayed shear failure of RC slabs subjected to vertical soil pressures and the time-dependent creep-shrinkage of structural concrete. Special attention is directed to the delayed shear cracking which was actually found in real underground box culverts over the service life. The delayed shear crack is experimentally reproduced in the laboratory as well as the multi-scale computational simulation.

INTRODUCTION

Kunieda et.al (2014) reported that top slabs of shallow underground RC box culverts were seriously deformed with numerous cracking. After a few decades of service, the deflection of the top slab exceeded approximately 3 to 10 times the design prediction by the conventional codes for practice as shown in Figure 1(a). Large numbers of cracks at the inner surfaces of tunnel have also been observed as shown in Figure 1(b). The largest crack width near the haunch is 0.9mm, which is more than three times the allowable value specified (Standard Specifications for Concrete Structures – 2007 (2007)). Through the analytical approach in consideration of migration of moisture and associated shrinkage, the authors reported that long-term excessive



(a) Deflection of the top slab (b) Cracks on the top slab

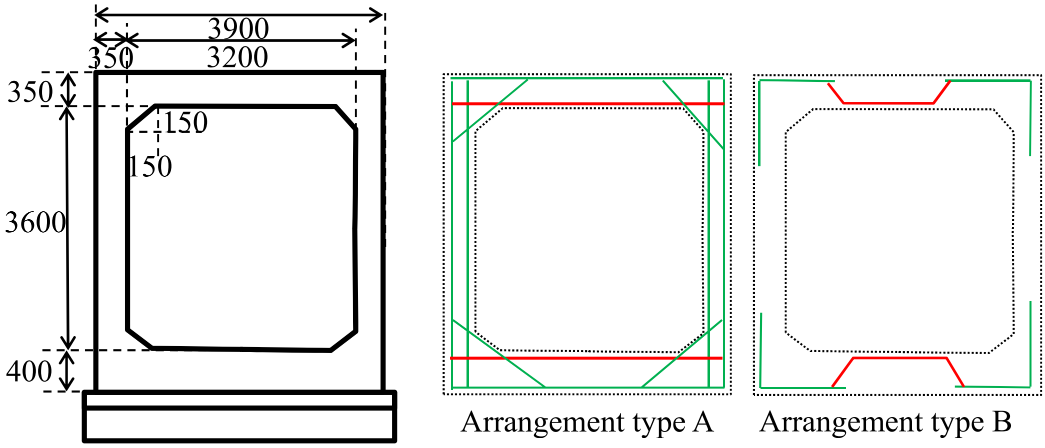
Figure 1 Excessive deflection and cracks of the culvert

deformation may attribute to synergy effects accompanying delayed shear failure owing to the vertical soil pressure, which can be accelerated by shrinkage and creep of structural concrete.

This conclusion is partially supported by the past studies, i.e., concrete's shrinkage and creep of the top slab possibly increases in the vertical earth pressure (Abhijit 1991, Richard 2005) acting on underground culverts caused by both uneven settlement of the foundation and RC structural deformation as a coupled action. Furthermore, the shear capacity of the RC simple beam which takes the influence of drying shrinkage is known to be reduced up to about 85% compared to the one under the sealed conditions (Mitani et al. 2011). Then, this paper aims to verify the existence of the predicted delayed shear crack, and get basic information to assess the future risk and serviceability of the underground RC culverts in line with the durability mechanics.

TARGET CULVERT

The dimensioning and detailing of the tunnel section suffering from excessive deflection are shown in Figure 2. This culvert was constructed in 1982. The thickness of the top slab is 35cm and the height of the fill above the culvert is relatively low, ranging from 5.04m to 6.98m. The dry sand is used as for backfilling material. This culvert has been used for urban utility and cabling, and it is in service as well. In order to keep the stable local ambient conditions, air ventilation is conducted with blower fan machines, and the temperature is kept about 25±2 degree Celsius. Then, the internal surfaces of the culvert have been exposed to continuous drying (RH=30±10%). The outer surface exposed to soil foundation was kept almost wet during its whole life and the ground water level is about at half of the side walls. It is



a) Shape of the culvert

b) Arrangement of steel bar
*Red:D22, Green:D19
*Type A and Type B appears each other in the pitch of 150mm

Figure 2 Design detail of the culvert

observed by the periodical monitoring that the number of cracks in the culvert has been increasing and the crack width has also become wider with time. Some cracks have reached reinforcing bars, but the steel corrosion is not observed at this moment because of less supply of moisture due to dry states. As a matter of fact, water leakage was found at several locations inside the culvert, but they are not from the top slab but the side walls and construction joints.

Characteristic values of concrete used are examined by the back-check tests of the mix proportion, and it is compared with the specified design values as shown in Table 1. Actual water to cement ratio of concrete mixture was larger than the design value, and both the compressive strength and Young's modulus are lower than the design specification. The characteristics of reinforcing bars are also examined, and its results are summarized in Table 2. The young's modulus of reinforcing bars is lower than the design value although the yield strength is larger. Working strains of the reinforcing bars on the top slab were measured by the stress release technique of destructive testing, and they are about 1000 micro in tension and it is in the elastic range.

Filled sand is cohesive, and N-value (standard penetration test) of the surrounding ground is 1 to 5 on the top slab and 0 to 2 at both sides of the culvert. From the test result of the grain size distribution, it is found that the surrounding ground consists of 4% coarse aggregate, 59-69% fine aggregate and 27-37% silt powder. The power ratio is a little bit larger than that of the normal ground. It is also confirmed that the culvert is surrounded by fully saturated ground.

Table 1 Estimated mix proportion of the concrete

		Test result	Reference
Compression Strength(N/mm^2)		24.2	Design: 24.0
Young's modulus (kN/mm^2)		16.6	JSCE standard specification:25.0
Mix Proportion	Maximum size of gravel(mm)	20-25	Design: 25
	Cement(kg/m^3)	393	Design: 285
	Water(kg/m^3)	248	Design: 154
	Fine aggregate(kg/m^3)	643	Design: 809
	Coarse aggregate(kg/m^3)	976	Design: 1076
	Water to cement ratio(%)	63.0	Design: 54.0
Fine pore	Total pore volume(ml/g)	0.129	-
	Air contents(%)	23.9	-
Carbonation depth(mm)		38.9	Cover depth: 58.6mm

Table 2 Stress condition of the reinforcement bar in the top slab

Section	Section 1	Section 2	Reference
Bar diameter	24.2		-
Estimated strength category	16.6		-
Young's modulus (kN/mm^2)	180	178	JSCE standard specification:200
Yield strength(N/mm^2)	391	391	JSCE standard specification:295
Measured stress(N/mm^2)	151	170	-
Corrosion	No	No	-

VERIFICATION FROM MATERIAL ASPECTS

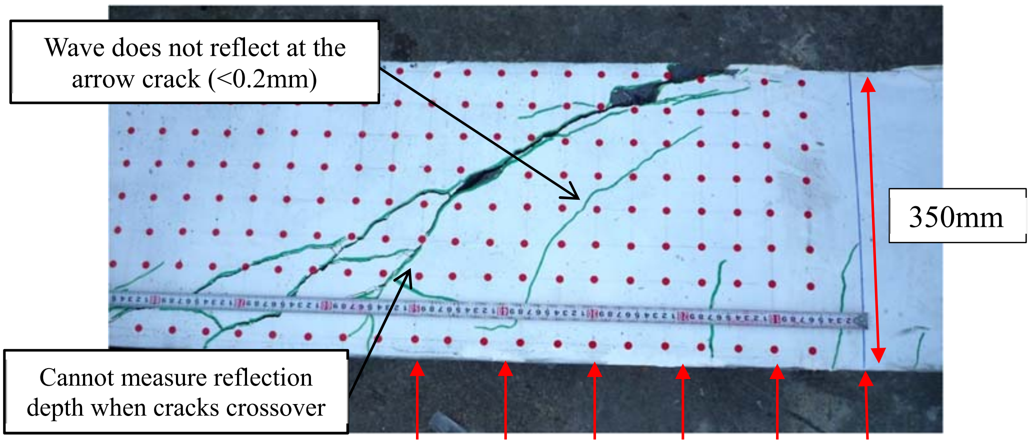
As the first step, the loading condition to the RC culvert, which may possibly cause the observed crack, is discussed. The vertical soil pressure on the top slab was inversely calculated so that the computed crack width and its spacing may match the observed reality by using the in-plane flexural theory. Here, the magnitude of drying shrinkage was simply derived from the total summation of the individual crack's width. In this inverse analysis, out of plane action was neglected.

The inverse analysis indicates the soil pressure as about 3 times large as the design value. If it is true, the reinforcing bars should be close to yield or more. Even if the horizontal conferment is assumed to be 0 to 0.4 times as large as the design value, the vertical load is limited at most 2.5 to 2.5 times large. It implies that the in-plane flexural theory never comes up to the real excessive deflection even though creep and shrinkage of concrete are taken into account. It seems quite probable that other unconcerned and uninvestigated factors like non-uniform soil pressure and/or delayed shear crack propagation may unavoidable impacts as Kunieda et al. (2014) pointed

(a) Light from the span center (b) Light from the hunch side

→Same crack is shoot, but shade appears only in (a) because of the gap.

Figure 3 Transverse gap on the crack in the top slab



Reflection depth(mm)	OUT	256	286	303	333	357
True value(mm)	-	260	290	310	350	350

Figure 4 Verification of the elastic wave reflection test

out in the previous short discussion before the following destructive testing.

DETECTION OF DIAGONAL SHEAR CRACKING

In case of columns and beams on the ground, it is easy to detect the shear failure by visual inspection. But, for tunnels and culverts, it is impossible to directly see the diagonal shear crack. Then, for verification of the out-of-plane deformation which may be associated with diagonal shear crack propagation, the inner surface of the upper slab was carefully examined by finger-touching from inside of the culvert. The transverse gap was clearly felt by fingers as scratched or interlock, which means the

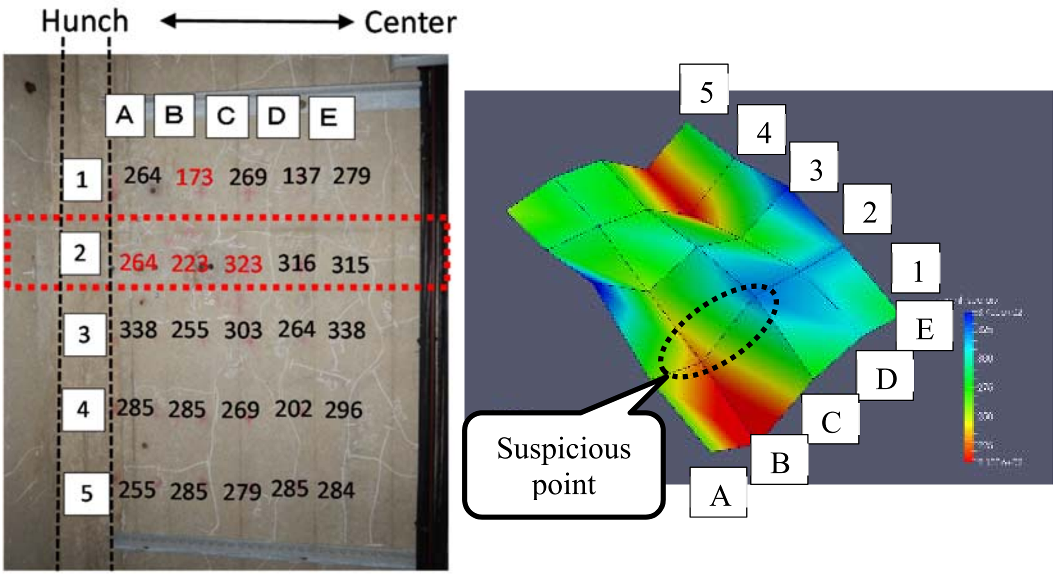


Figure 5 Contour map of the wave reflation depth in the culvert

out-of-plane deformation of cracked concrete as shown in Figure 3. This gap was observed larger near the hunch side where the greater shear force is thought to be applied than the center span. Then, this crack is highly estimated to be an extreme end of diagonal crack planes.

This transverse gap can be easily detected as well by shadows of the skew illumination as shown in Figure 3. In the case of flexural cracks without the transverse gap, no shadow is made no matter how much directions the illumination is applied. This is some sort of visual inspection to detect the out-of-plane alone.

The elastic wave reflection test (e.g. Schabowicz et al. (2012)) was also conducted at several points on the line normal to the culvert axis. If the crack is vertical bending one, the acoustic wave should reflect at about 350mm depth (opposite side of the slab thickness). But, if the crack would be inclined to the centroid axis of the slab, the reflecting depth will be smaller. Validity of the method was examined in advance by using the beam which failed in the mode of shear. Figure 4 shows the depth of wave reflection point which agrees well with the crack depth from the bottom side of the beam.

Figure 5 is the detected height map of the wave reflation depth in the culvert, and it is found that there exist some points where the wave reflection changes significantly around the point. At these points, diagonal shear crack is suspected to be present. Around the most suspicious point between 2-B to 2-C as shown in Figure 5, several micro-bore holes were drilled in about 300mm depth, and the inner surfaces were scanned by the stick scanner (Zacoeb et al. (2007)). The scanned images are shown in Figure 6, and a crack across the hole is found from this image. The enclosed shape of the crack plane is expected from the depth where the crack intersects the hole. This seems to be a typical diagonal shear crack, and it does not reach the flexural compression zone.

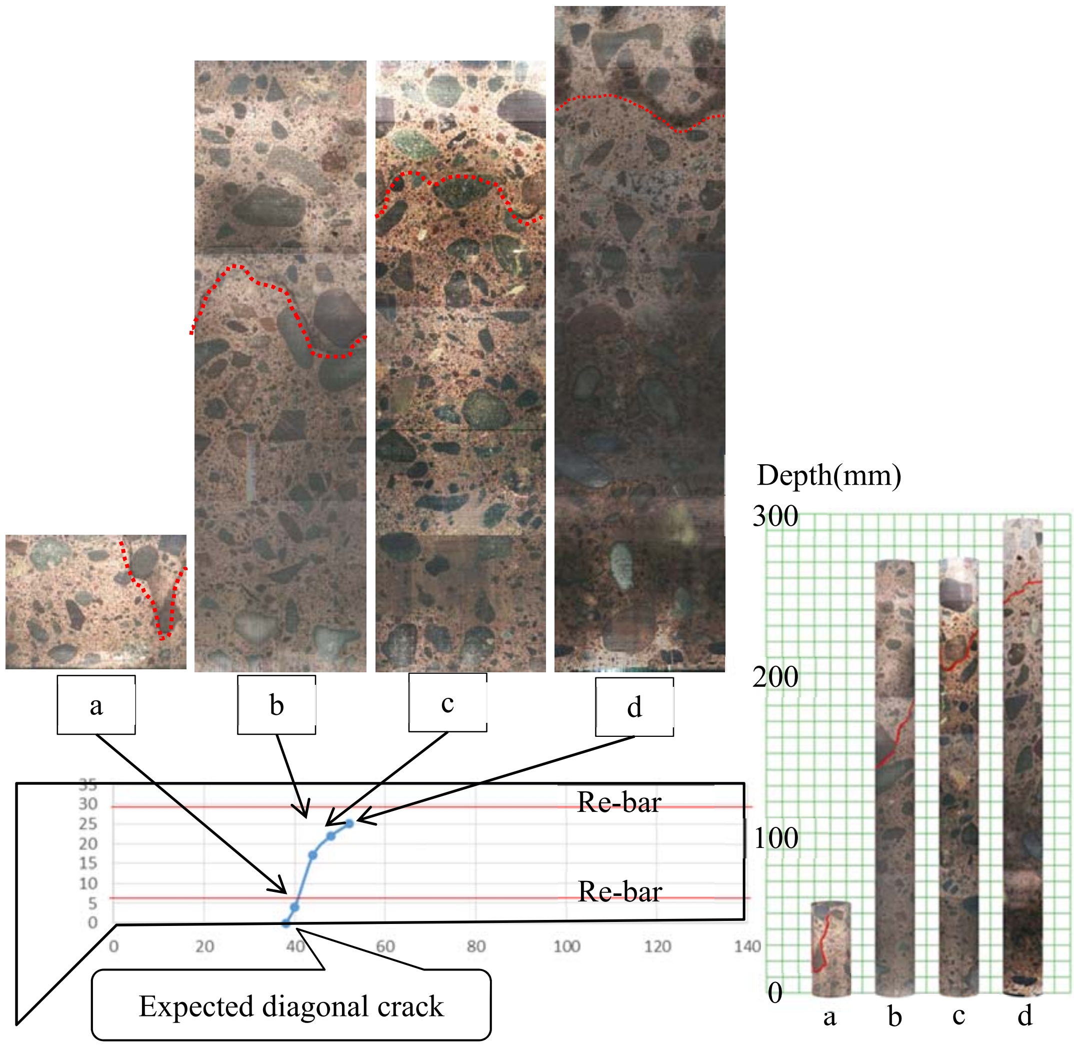


Figure 6 Image of the inner surface of the hole and expected diagonal shear crack in the top slab

With these observations, it can be concluded that the excessive deflection is caused not only by the flexural deformation associated with shrinkage and creep of concrete, but also by the propagation of diagonal shear cracks which lead to out-of-plane displacement. It is assumed that the diagonal shear crack gradually extends for about 30 years, accompanying the top slab deflection.

From the finger-touching examination of the crack and elastic wave reflection test, the diagonal shear crack seems to be formed at many places in the culvert. At this moment, they are formed locally, and not fully linked along the culvert axis. Because the vertical load on the diagonal crack position can be redistributed along the culvert axis by the three-dimensional effect, the safety of the culvert can be maintained even though the diagonal crack is locally formed. Detailed coupled analysis of the whole structures and soil foundation under static and dynamic conditions will be needed for upgrading the maintenance strategy of existing infrastructures.

CONCLUSION

The existence of the delayed shear crack is confirmed by several tests in the shallow RC box culvert. The excessive deflection of the top slab in the culvert is caused by not only by the shrinkage and creep of the concrete but also by the slip on this delayed shear crack. In order to assess the safety of the structure under static and dynamic condition, further experiments and analyses are necessary based on the facts found in this research.

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