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Determination of the repair grout volume to fill voids in external post-tensioned tendons

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Abstract. Recently, investigated failures of external post-tensioned (PT) tendons have called attention to the corrosion of strands in PT bridges, and the prevention of ongoing corrosion is required to secure their structural integrity. Since voids inside ducts can be a source for the ingress of water or deleterious chemicals, the vacuum grouting (VG) method and a volumeter for estimating amount of repair grouts were employed to fill voided ducts. However, the VG method is expensive and time-consuming for in-field application because it requires an air-tight condition of entire ducts. Thus, latest research assessed three different repair grouting methods, and the pressure vacuum grouting (PVG) method was recommended in the field because it showed good filling capability in voided ducts and did not require an air-tight condition. Thus, a new method is required to estimate the volume of repair grouts because the PVG method is not applied in air-tight ducts. This research assesses the relationship between voided areas on ducts identified with soundings and required grout volume for repair using experimental results. The results show that the proposed equations and assumptions for estimating repair grout volume provide a sufficient amount of repair grouts for filling voided ducts.

Keywords: post-tensioned bridge; void; repair grouting; volume of repair grouts; sounding inspection

1. Introduction

Post-tensioned (PT) segmental bridges have been commonly constructed because PT tendons make them possible to have longer and slender spans, which are more aesthetically pleasing. However, recently investigated failures of PT tendons have called attention to the corrosion of PT tendons because tendon corrosion may lead to the collapse of PT bridges (Pearson-Kirk 2003, Raiss 1995, Schokker *et al.* 2001). The sudden failures of the Bickton Meadows Footbridge and the Yns-y-Gwas Bridge in UK have raised concerns about the durability of PT bridges. Recent investigations found failures of external PT tendon in the Mid-Bay Bridge and the Varina-Enon Bridge in USA, and the severity of corrosion in PT systems was emphasized (Corven 2001, Pielstick 2002, Sprinkel and Napier 2008). Therefore, research on how to prevent strand corrosion of PT systems is required

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to ensure bridge integrity and safety.

Grouting in PT systems is necessary for structural performance. Park studied the need for grout in post-tensioned tendon ducts by comparing grouted and unbonded post-tensioned tendons (Park 1975). His study showed that cement-based grout significantly reduces corrosion in PT tendons. Furthermore, tendons that are not grouted tend to weaken under repeated loading. Further, ungrouted tendons can induce cracks around the tendon that propagate and eventually result in brittle failure. O'Neal and Schupack tested post-tensioned I-beam specimens having different end anchorage protections (O'Neil and Schupack 1997). These specimens were transported to Treat Island, Maine in 1961 to evaluate the behavior of PT tendons in severe corrosive conditions. While some end anchorage protections failed, the failures did not result in an overall tendon failure. However, unbonded tendons using grease or paper wrap showed severe corrosion which eventually led to tendon failure during exposure. For this reason, grouting in PT system is desirable for ensuring good structural performance.

Voids in grouted PT ducts are fairly common. According to previous studies, void areas in the grouted ducts exist in 35% of the entire duct areas in Japan (Woodward and Miller 1990). In another study, 30% of tested ducts in 1000 post-tensioned bridges in the UK contained voids while 19% of inspected bridges in the United States were found to have some voids (Pearson-Kirk 2003). Based on the investigation of Texas Department of Transportation (TxDOT), nearly 80% of investigated anchorage parts in a PT bridge included corrosion and voids, and 30% of investigated anchorage parts were determined to have severe corrosions (TxDOT 2004). Voids, in these studies, usually formed at the top surface of the investigated ducts and near the end anchorages. These voids are formed by entrapped air pockets, grout bleeding, and improper grouting (Woodward and Miller 1990, PCI 1997).

Pearson-Kirk noted that the main cause of strand corrosion was the ingress of water or deleterious chemicals from damaged ducts (Pearson-Kirk 2003). Based on the previous investigation of PT bridges, he concluded that local voids were not critical in strand corrosion. However, Pillai performed corrosion tests for strands and found that small local voids can impact the performance of strands (Pillai 2009). As a result, filling voided ducts can be an option to prevent strand corrosion of PT system.

However, less research has been executed for repair grouting of voided ducts. In 1995, Raiss recommended the vacuum grouting method for repair, but it can be ineffective when the ducts are not in an air-tight condition (Raiss 1995). Moreover, most studies recommend the vacuum grouting method for filling large voids in ducts (Corven 2001, Pielstick 2002, VSL 2002, FHWA 2004, Shoji *et al.* 2003). The Federal Highway Administration (FHWA) recommended the application of vacuum grouting under pressure (FHWA 2004); however, this method is very costly and time-consuming because it needs to have an air-tight duct for successful repairs. In addition, it is difficult to create and maintain an air-tight condition throughout the entire duct when limited and confined spaces are provided inside the box girder of PT bridges. Recently, Im *et al*. compared three repair grouting methods, vacuum grouting (VG), pressure grouting (PG), and pressure-vacuum grouting (PVG). They concluded that the PVG method is the most effective for filling voided ducts because it does not require an air tight condition (Im *et al.* 2010a).

The volume of repair grout can be estimated using a volumeter, an instrument that measures the volume of voids in ducts, using air pressure (FHWA 2004). However, the use of a volumeter requires that ducts are in sealed conditions to correctly estimate void volumes. While volumeters are equipped with some leak compensation abilities, errors might be occurred when ducts are not sealed at all. Based on the experimental results in latest research performed by Im *et al.* repair grouting may have to be performed from each end for this to be accomplished in the field as test results have indicated that repair grouts cannot fill all voids in the entire tendon at one time (Im *et al.* 2010a). However, a volumeter is capable of estimating the entire volume of an external tendon when the air-tight condition is created; that is, additional measurement in the same tendon is required after hardening the grouts repaired from an end of the tendon. Therefore, alternative methods for measuring the volume of voids are required in accordance with the repair grouting procedures.

For the inspection of voids in external PT ducts, a sounding inspection is generally performed to identify the existence of voids because it is a relatively fast and easy inspection (Corven 2001). Im et al. evaluated the effectiveness of sounding inspection using transparent ducts, and voided areas on ducts identified by soundings were compared against actual void conditions (Im *et al.* 2010b).

Based on the previous study, this research first assessed the relationship between voided areas by sounding inspection and actual voids through transparent ducts. Because the surface area of actual voids on ducts are related to the volume of voids inside the ducts, this research then assessed the experimental results to identify this relationship each other. Finally, equations and procedures to determine the sufficient amount of repair grouts to fill the voided ducts are proposed for the PVG method.

2. Experimental test setup, methods, and assessment

External PT tendon systems are typically installed in a harped shape in the field to reduce or eliminate positive flexural moments acting on the mid-span and negative flexural moments at both end-spans in continuous span bridges; thus, enabling bridges to have longer and more slender spans. Recent investigations of PT bridges indicated that voids usually exist in the external PT systems near end anchorage zones. Thus, these conditions are considered in the full scale test setup in this research.

2.1 Full scale test setup

To simulate voids inside external PT tendons in the field, half of a harped tendon system is designed and fabricated. A schematic of the experimental specimen is shown in Fig. 1.

This full-scale experimental setup is comprised of 19 strands tensioned to 0.3% of their ultimate tensile strength (0.8 ksi, 5.52 MPa) to straighten the strands and simulate field conditions. The strands are located inside a transparent acrylic duct with an inside diameter of 4 inches (0.1 m).

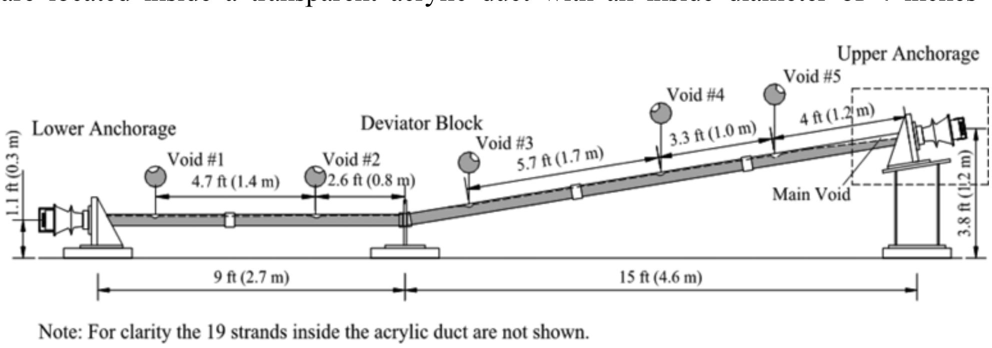

Fig. 1 Full-scale experimental setup showing void locations

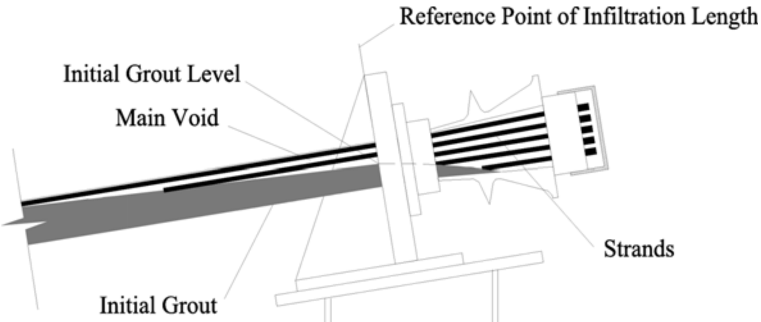

Fig. 2 Close-up view of void near anchorage

After stressing the strands, the interstitial spaces between the stands and duct are filled with Class A grout (cement and water with a water-cement ratio (w/c) of 0.44) to consider the effect of bleeding. Artificial voids are then intentionally created in the top anchorage zone and at five locations along the duct to simulate improper grouting procedures in the field (Fig. 1). The main void near the top anchorage zone is formed by filling the grout only up to the 'initial grout level' as indicated in Fig. 2. To simulate entrapped air pockets, the five void locations along the duct system are intentionally created by extracting grout from these locations using a vacuum pump and flask.

As shown in Fig. 1, the main void at the top anchorage zone and the five other small voids along the duct are connected by a top surface void line along the duct. These void lines are called "bleed lines" (also known as "bug holes") and are spontaneously formed by the evaporation of bleed water from the grout (PCI 1997). A total of 15 experimental specimens are assessed for identifying the relationship between the sounding inspection method and the repair grout volume.

2.2 Sounding inspection test and assessment

Based on the research performed by Im *et al.* the void maps by the sounding inspection method showed close correlation with the void profiles by the visual inspection through transparent ducts (Im *et al.* 2010b). The presence of voids was identified by detecting an irregular and drummy sound while tapping. In the test, soundings were recorded at every inch in the surveyed intervals (1 ft, 0.305 m) of specimens. Following this sounding inspection method, void profiles of full-scale test specimens were drawn on "void mapping sheets". For example, irregular soundings are recorded on the "unrolled drawing" of PT ducts as shown in Fig. 3 and Fig. 4.

Visual inspections were performed through the transparent ducts to assess the accuracy of the

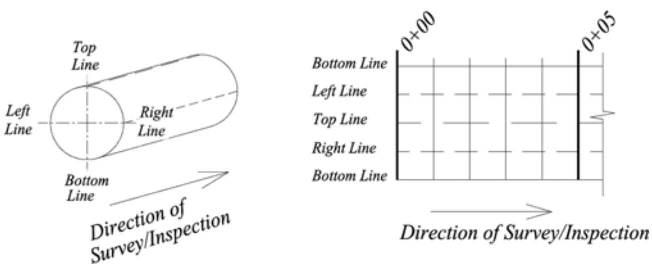

Fig. 3 Unrolled drawing of PT ducts in the "Void Mapping"

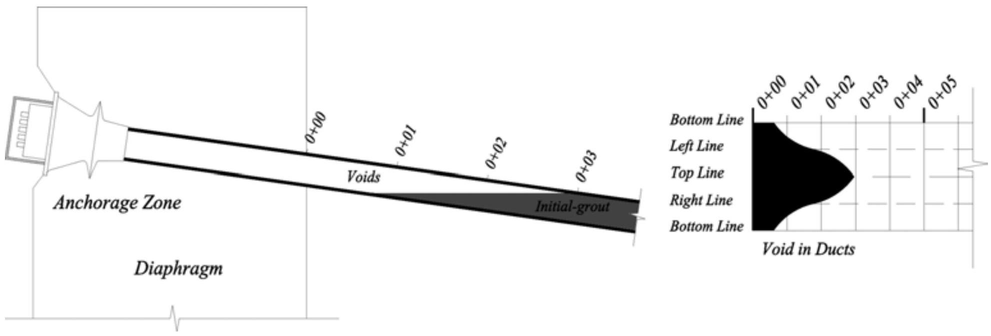

Fig. 4 Marking voids on the “Void Mapping Sheet”

sounding inspections. The void maps obtained from the visual and sounding inspection were assessed in a program computing areas on a scaled map, and the void area at every one-foot (0.305 m) interval was determined.

2.3 Assessment of repair grout volume

To identify the relationship between the area obtained from the sounding inspection and void

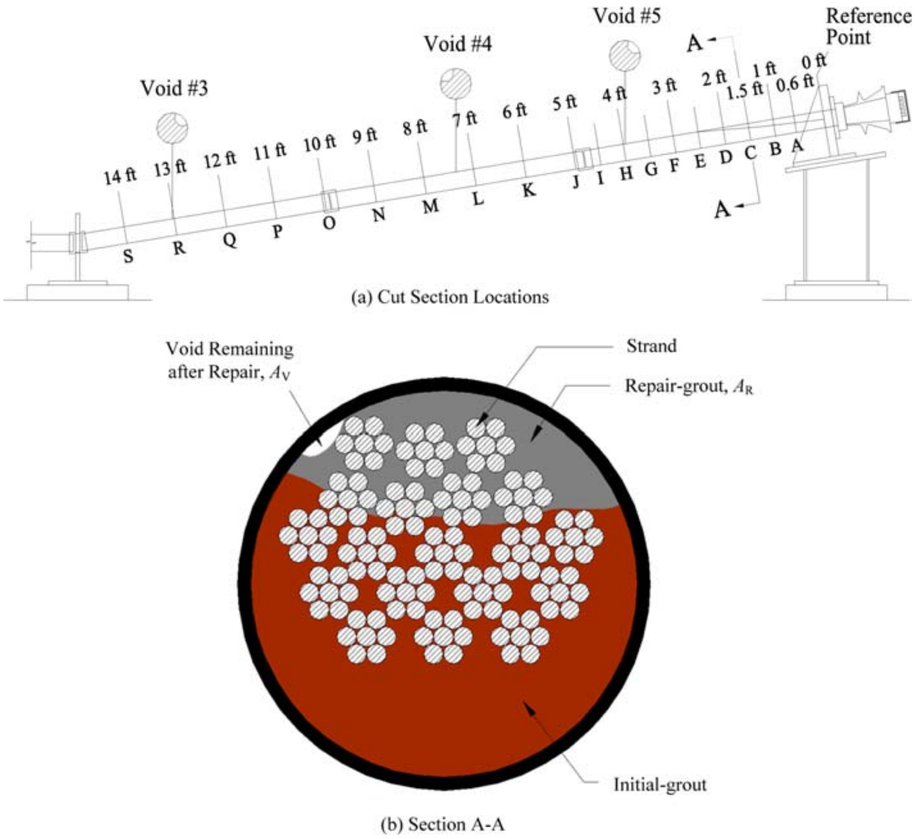

Fig. 5 (a) Cut section locations of repaired ducts (b) and cut section of A-A

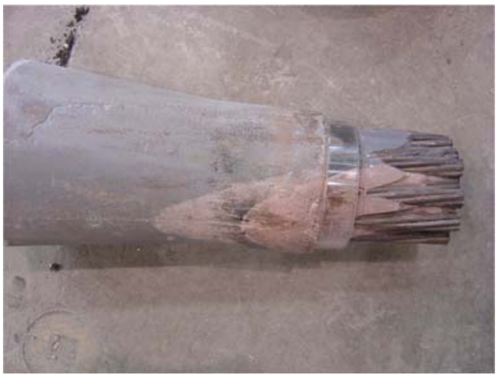

Fig. 6 Inside view of bearing plate (Trumpet) after repair grouting

volume, this research assesses the amount of voids filled by a repair grout using an analysis of cut sections. Sections are cut using a band saw at the locations shown in Fig. 5(a). From the cut sections (Fig. 5(b)), the cut-section area of a repair grout, A_R, indicates initial voids before repair grouting. Thus, A_R of each cut section is estimated using figures in AutoCAD®, and the initial void volume along the duct is then computed. For cut sections, the approximate repaired volume is determined using the average void area at both ends multiplied by the cut length. Fig. 6 shows the inside view of a bearing plate for test specimens and a small amount of initial grouts was injected inside the bearing of every specimen. Thus, the void volume of the inside bearing plate is approximately considered as an empty bearing plate with 19 strands.

3. Experimental results

From the results of the research performed by Im *et al.* the linear relationship between voids obtained from the sounding inspection method and actual voids are provided (Im *et al.* 2010b). The void volumes predicted from the cut section analysis can be related with the actual voids identified through the transparent ducts. From these relationships, thus, repair grout volume can be determined by the sounding inspection method.

3.1 The relationship between sounding inspection and visual inspection

In previous research executed by Im *et al.* (2010b), the sounding inspection method and the visual inspection through the transparent specimen were performed to assess the accuracy of the sounding inspection method. The sounding inspection was carried out using steel impactors (Fig. 7) and Fig. 8 shows the initial void profiles identified by the sounding inspection and the visual inspection before repairing the specimen. The void profiles are calculated using AutoCAD®.

The scatter plots of the void areas per foot obtained from sounding and visual inspection ($A_{SI/ft}$ and $A_{VI/ft}$) are shown in Fig. 9. The analysis results exhibit a highly positive, linear correlation (correlation coefficient is 0.906) between the sounding and visual inspections. The linear regression equation of the scatter plots is as follows

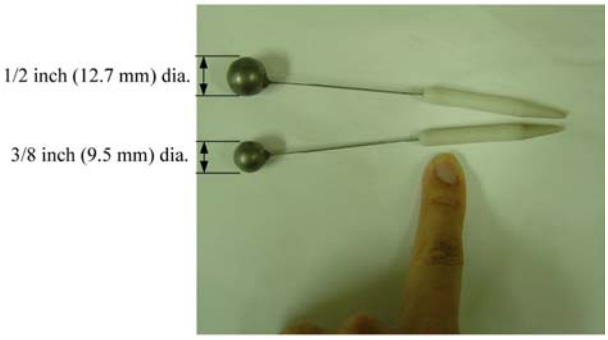

Fig. 7 Steel impactors for sounding inspection

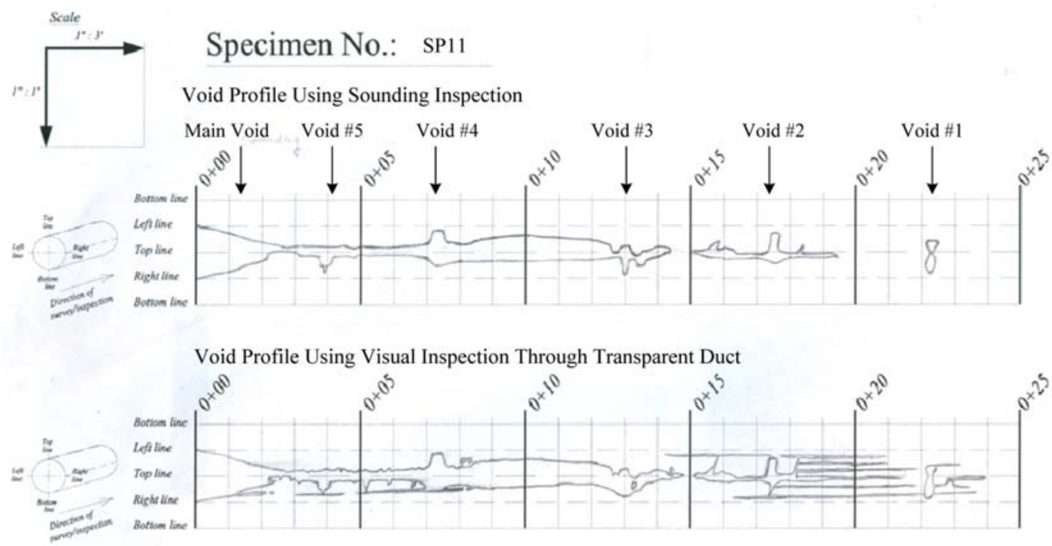

Fig. 8 Void map of specimen 11

$$A_{VI/ft} = 0.85A_{SI/ft} + 4.5$$
$$(A_{VI/ft} = 0.85A_{SI/ft} + 30 \text{ for SI unit}) \tag{1}$$

where $A_{VI/ft}$ is the area estimated by visual inspection, which is assumed here to be the actual void area per foot estimated on void mapping sheet, in inch^2 (cm^2 for SI unit) and $A_{SI/ft}$ is the area estimated by the sounding inspection in inch^2 (cm^2 for SI unit). To prevent the underestimation of voids, the prediction upper bound (U.B.) equation for a 0.05 level of significance can be used as follows

$$A_{VI/ft}' = 0.85A_{SI/ft} + 19 \text{ (U.B.)}$$
$$(A_{VI/ft}' = 0.85A_{SI/ft} + 120 \text{ (U.B.) for SI unit}) \tag{2}$$

Through the sounding inspection, $A_{SI/ft}$ is obtained as follows

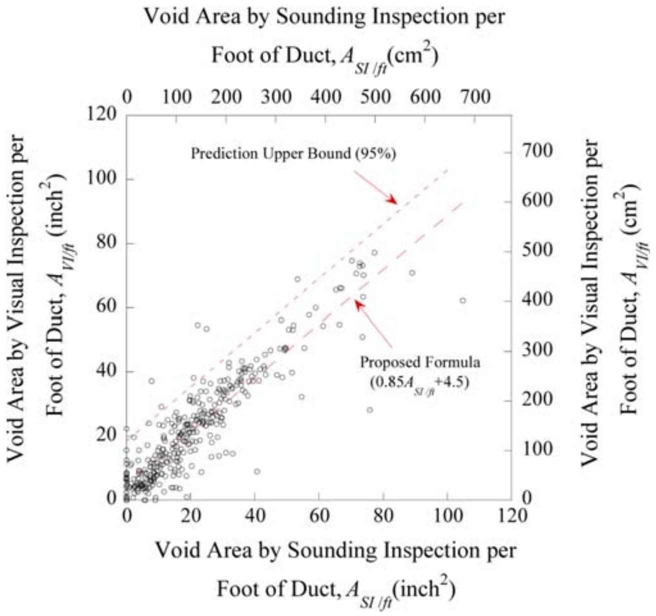

Fig. 9 Scatter plots between the void areas per foot obtained from sounding and visual inspections

$$A_{SI/ft} = A_{SI}/l_{void}$$
$$(A_{SI/ft} = 0.3048\ A_{SI}/l_{void} \text{ for SI unit}) \tag{3}$$

where A_{SI} is the total void area estimated by the sounding inspection in inch^2 (cm^2 for SI unit) and l_{void} is total void length on void mapping sheet in foot (m for SI unit).

3.2 The relationship between visual inspection and void volume

In this research, estimates of the required volume for repair grouting are made using the relationship between the data obtained from visual inspections and the volume obtained by cut section analysis. However, the experimental specimens are too short to provide the required grout volume in the field. Thus, this research estimated average void volume in bleed line per unit length, one foot (0.3048 m), and computed the required grout volume for repair by multiplying the length of voids. To ensure sufficient grouts for repair, less than partially filled parts, void areas that exceed the "Left Line" and "Right Line" on void mapping sheets, are assumed as empty.

To predict the relationship between the surface area on the voided ducts and the void volume inside the duct, this research assumes that the initial grout maintains a level in each cut section. Fig. 10 exhibits the cut sections after repair grouting and the initial grouts in each section seem to be level whereas the section H shows an irregular shape due to the created artificial voids (void #4) in the specimen. Thus, an ideal relationship between surface area on voided duct and void volume can be represented as shown in Fig. 11. The plot corresponds to a polynomial curve, so the regression for experimental data is determined with a cubic curve.

From the volumetric estimations of repaired grouts in the test specimens, the scatter plots between

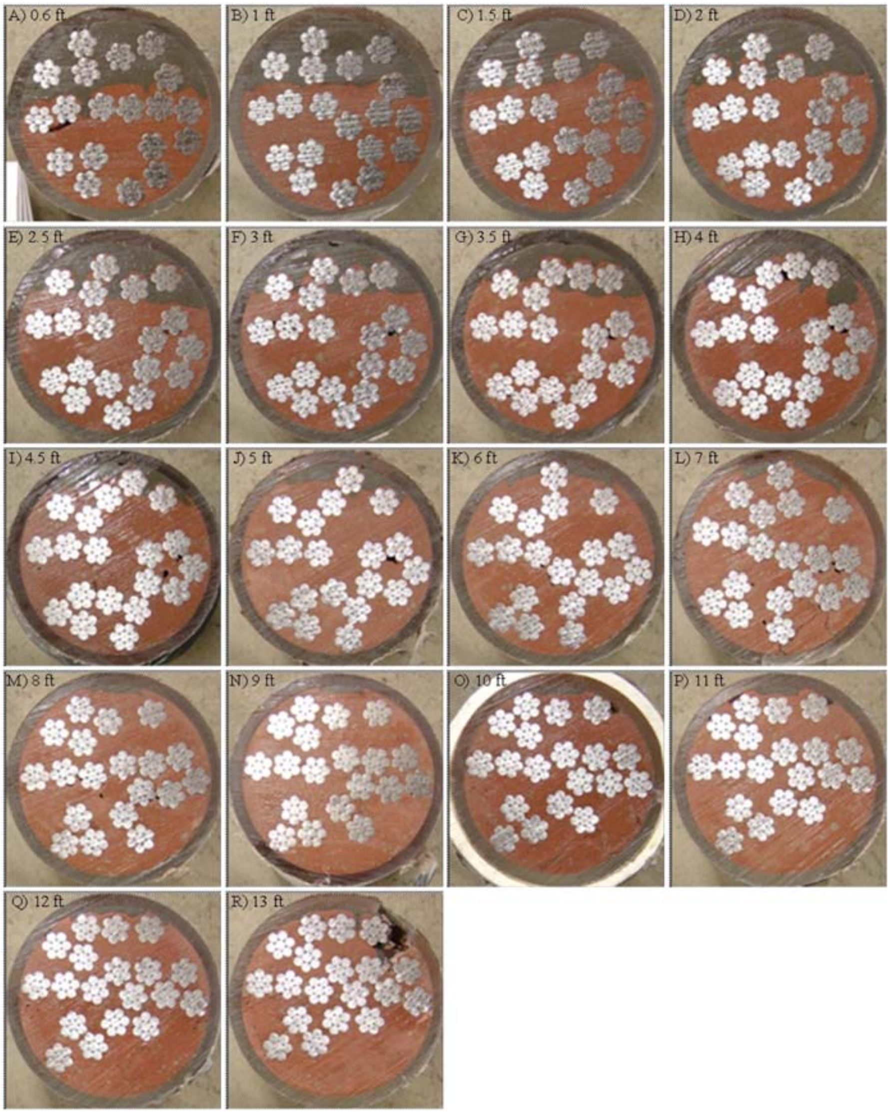

Fig. 10 Cut sections of specimen 11 for the filling analysis of repair grout

void areas per foot by visual inspection and the required volume of repair grouts per foot used for the specimens are provided in Fig. 12.

From the relationship between void areas per foot from visual inspection and the void volume repaired per foot, the cubic regression curve is obtained as

$$V_{req/ft} = 4 \times 10^{-5} \, (A_{VI/ft} + 16)^3$$
$$(V_{req/ft} = 3 \times 10^{-6} \, (A_{VI/ft} + 90)^3 \text{ for SI unit}) \tag{4}$$

where, $A_{VI/ft}$ is the estimated area per foot by visual inspection in inch^2 (cm^2 for SI unit) and $V_{req/ft}$ is

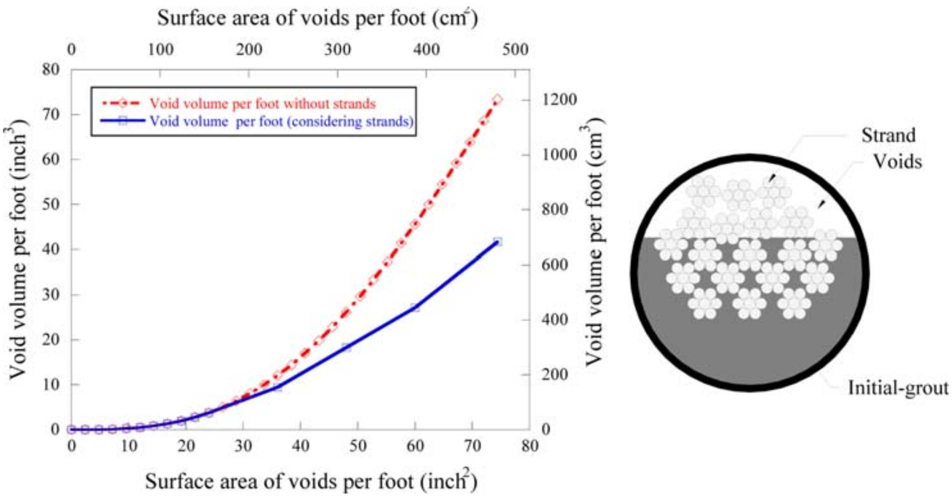

Fig. 11 Relationship between surface area of voids and void volume when the initial grouts are level in sections

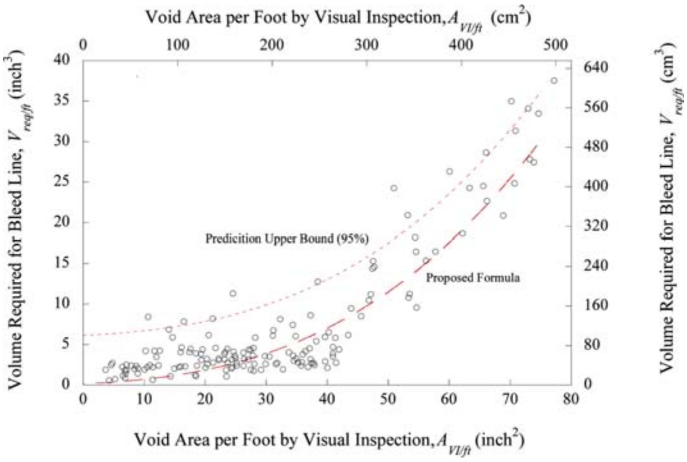

Fig. 12 Cubic regression curve and prediction upper bound for relationship between the void areas per foot from visual inspection and the void volume repaired per foot

the estimated repair volume per foot of the specimen in inch^3 (cm^3 for SI units). To ensure enough grout for repair, the prediction upper bound (U.B.) equation for a 0.05 level of significance is given by

$$V_{req/ft}' = 4\times10^{-5}(A_{VI/ft}+16)^3+6 \text{ (U.B.)}$$

$$(V_{req/ft}' = 3\times10^{-6}(A_{VI/ft}+90)^3+100 \text{ (U.B.) for SI unit}) \qquad (5)$$

3.3 Determination of repair grout volume using the sounding inspection

Using Eqs. (2) and (5), the repair grout volume per foot can be estimated from the void profile assessed by the sounding inspection method. Although the sounding method was not performed by different inspectors and the human factor may affect the experimental results of the sounding inspection method, the proposed equations consider the prediction of an upper bound to prevent the underestimation of repair grout volume. The equation of the repair volume per foot for the bleed line, which does not contain the volumes of bearing plate and embedded ducts, is defined as follows

$$V_{req/ft} = 4 \times 10^{-5}(0.85 \times A_{SI/ft} + 35)^3 + 6$$
$$(V_{req/ft} = 3 \times 10^{-6}(0.85 \times A_{SI/ft} + 210)^3 + 100 \text{ for SI unit}) \tag{6}$$

where, $A_{SI/ft}$ is the estimated area per foot by sounding inspection in inch^2 (cm^2 for SI unit) and $V_{req/ft}$ is the estimated repair volume per foot of the specimen in inch^3 (cm^3 for SI units).

Thus, total required volume for ducts can be estimated multiplying the total length of voids

$$V_{req} = V_{req/ft} \times l_{void}$$
$$(V_{req} = V_{req/ft} \times l_{void}/0.3048 \text{ for SI unit}) \tag{7}$$

where, l is the total length of void in foot (m for SI unit) and V_{req} is the estimated repair volume of the specimen in inch^3 (cm^3 for SI units).

Based on the cross sections of each test specimen the repair volume per foot is obtained to estimate the void volume of bleed lines. However, this relationship does not include the void volume contained in the embedded ducts and the bearing plate in the diaphragm; these areas cannot be examined using the sounding inspection method. To ensure that sufficient grout is prepared, volume estimates of the repair grout should be made assuming that the embedded ducts and bearing plate contain no grout. From bearing plate designs and diaphragm thicknesses, bridges have different grout volume requirements for anchorage zones. Thus, the void volume in the bearing plate and embedded ducts has to be added to Eq. (7) for field application.

Fig. 13 provides examples of void profiles obtained from the sounding inspections. While this inspection shows the existence of voids, it lacks the ability to show void size and the condition of the strands inside. Hence, a detailed inspection using a borescope would be beneficial to assess voids and strand corrosion (Trejo *et al.* 2009a, Trejo *et al.* 2009b). From a detailed inspection using a borescope, it may be determined whether tendons need repair or not. In both examples seen in Fig. 13, it is assumed that repair grouting might be needed. Although this volume may be different in actual structures, the obtained volume can be simply determined from the sounding inspection to ensure sufficient volumes for repair.

In the case of the example in Fig. 13(a), the value of A_{SI} can be estimated from 3 ft (0.91 m) to 10.2 ft (3.07 m). Note that the void profile between 0 ft (0 m) and 3 ft (0.91 m) represents a nearly

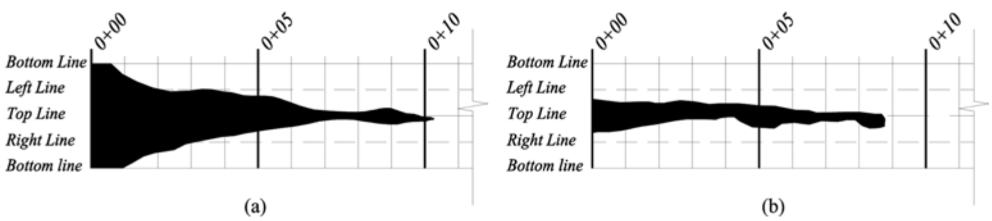

Fig. 13 Examples of void profiles obtained from sounding inspection method

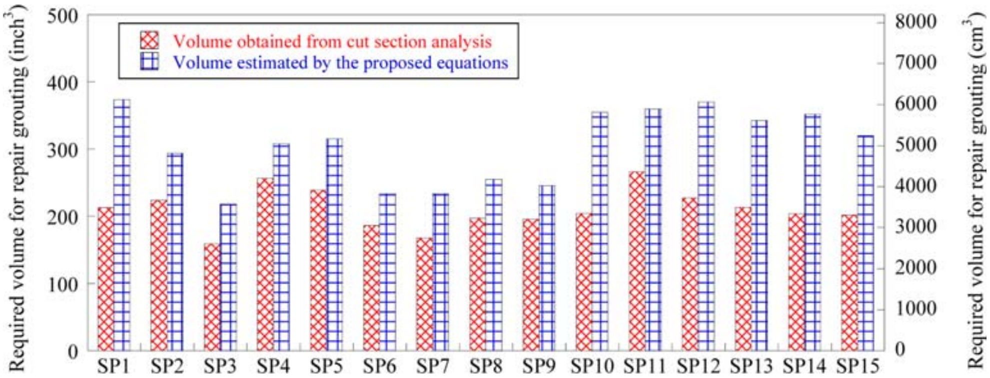

Fig. 14 Comparison between the void volume obtained from cut section analysis and estimated repair grout volume by proposed equations

empty duct. To ensure sufficient amounts of repair grout, void areas exceeding the "Left Line" and "Right Line" are considered as empty. Thus, the bearing plate, the embedded ducts in the diaphragm, and an additional 3 ft (0.91 m) along the ducts are considered to be empty in this case. To estimate the area per foot of the sounding inspection, $A_{SI/ft}$, the total void area, A_{SI}, from 3 ft (0.91 m) to 10.3 ft (3.14 m) is divided by the total length of the voids, l_{void}. The repair grout volume per foot, $V_{req/ft}$, can be obtained from Eq. (6). Then, the total required volume, V_{req}, can be determined using Eq. (7). The volumes of the empty bearing plate and ducts have to be estimated and added to V_{req} to provide the total required volume for repair grouting.

In the case of the example in Fig. 13(b), the value of A_{SI} can be estimated from 0 ft (0 m) to 9.7 ft (2.92 m). Note that the bearing plate and embedded ducts in the diaphragm are considered to be empty. The estimated A_{SI} can be used to determine $A_{SI/ft}$ in Eq. (3) and V_{req} can be estimated using Eqs. (6) and (7). The volumes of the bearing plate and duct embedded in the diaphragm are estimated assuming they are empty. The total required volume can again be obtained by adding these two volumes.

Note that Eq. (6) for estimating the volume required for repair can be applied in the field when external tendons are contained in 4-inch (0.1-m, inside diameter) ducts and void profiles are determined using sounding inspections. Based on the previous research (Im *et al.* 2010b), a void profile developed using a sounding inspection method can be used to predict the required grout volume for repair, as well as appropriate locations for detailed inspections using a borescope.

Using the proposed equations and assumptions, repair grout volumes for 15 test specimens are estimated to verify the equations. Fig. 14 exhibits void volumes obtained from the cut section analysis and void volumes predicted using the proposed methodology. Although the proposed approach overestimates the volume by about 60-70% in some cases such as SP1 and SP10, it is still promising. First, the provided method does not require an air-tight condition of an entire PT system while a volumeter needs the air-tight condition. Secondly, voids in a harped external PT tendon cannot be repaired at one time repair process (Im *et al.* 2010a). Thus, the volume estimation using a volumeter is not appropriate because it cannot estimate a half of the voided volume in the entire PT tendon. Therefore, the proposed method seems to be more acceptable for applying the PVG method, and the proposed equation can provide and ensure a sufficient amount of repair grouts to fill voided ducts.

4. Conclusions

The sounding inspection method has been commonly used to inspect voided ducts in the field due to its ease of testing. In addition, the latest research has assessed the effectiveness of the sounding inspection method using transparent ducts, and void profiles obtained from sounding inspections have shown a good agreement with actual voids in ducts.

This research provides an alternative method to estimate the repair volume required in voided ducts using sounding inspection. Although the currently used volumeter can estimate the void volume in ducts accurately, significant preparation may be necessary to seal ducts to ensure accurate estimates of the entire duct volume. As a result, this research estimated the relationship between void profiles through visual inspections and the volume of repair grout in ducts. The repair grout volume was assessed using cut section analysis. Through discovered relationships between sounding and visual inspections, the void profile found by a sounding inspection can now sufficiently approximate the required volume of repair grouting.

As shown, the sounding inspection method can be applied as an effective inspection tool in the field and can be used to estimate void volume for repair grouting. However, this approach may not be cost effective for performing inspections of a small box girder bridge where a walkthrough inspection is limited due to low height.

References

Corven, J.A. (2001), *Mid-Bay Bridge Post-tensioning Evaluation – Final Report*, Florida Department of Transportation (FDOT), Corven Engineering Inc., Tallahassee, FL.

FHWA (2004), *Post-Tensioning Tendon Installation and Grouting Manual*, Federal Highway Administration (FHWA), Washington, DC.

Im, S.B., Hurlebaus, S. and Trejo, D. (2010a), "Effective repair grouting methods and materials for filling voids in external post-tensioned tendons", *Transport. Res. Record: J. Tran. Res. Board*, **2172**, 3-10.

Im, S.B., Hurlebaus, S. and Trejo, D. (2010b), "Inspection of voids in external tendons of post-tensioned bridges", *Transport. Res. Record: J. Tran. Res. Board*, **2172**, 115-122.

O'Neil, E.F. and Schupack, M. (1997), "Steel post-tensioning tendon behavior – up to 35-year marine exposure", *Proceedings of ASCE Structures Congress*, 324-328.

Park, R. (1975), "Post-tensioned tendons in prestressed concrete – to grout or not to grout?", *New Zealand Eng.*, **30**(11), 315-319.

PCI (1997), *Chapter 3: Fabrication and Construction, PCI Bridge Design Manual*, Prestressed Concrete Institute, Chicago, IL.

Pearson-Kirk, D. (2003), "The performance of post-tensioned bridge", *Role of Concrete Bridges in Sustainable Development – Proceedings of the International Symposium*, 129-140.

Pielstick, B. (2002), "Grouting of segmental posttensioned bridges in America", *Transport. Res. Record*, **1813**, 235-241.

Pillai, R.G. (2009), "Electrochemical characterization and time-variant structural reliability assessment of post-tensioned, segmental concrete bridges", Ph.D Dissertation, Texas A&M University, College Station, TX.

Raiss, M. (1995), "Post-tensioned concrete bridges: the UK debate", *Concrete Int.*, **29**(2), 23-26.

Schokker, A.J., Breen, J.E., and Kreger, M.E. (2001), "Grouts for bonded post-tensioning in corrosive environments", *ACI Mate. J.*, **98**(4), 296-305.

Shoji, N., Noritaka, S., Yasushi, K. and Koichiro, S. (2003), "Development of repair method for poorly grouting of PC structures", *Concrete J.*, **41**(11), 31-43.

Sprinkel, M. and Napier, C.S. (2008), "VDOT experience with grouted tendons in Varina-Enon precast segmental post-tensioned bridge", *Virginia Concrete Conference*.

Trejo, D., Hueste, M.B., Gardoni, P., Pillai, R., Reinschmidt, K., Im, S.B., Kataria, S., Hurlebaus, S., Gamble, M. and Ngo, T. (2009a), *Effect of Voids in Grouted Post-tensioned Concrete Bridge Construction,* Vol. 2, Texas Department of Transportation (TxDOT), Austin, TX.

Trejo, D., Im, S.B., Pillai, R., Hueste, M.B., Gardoni, P., Hurlebaus, S. and Gamble, M. (2009b), *Effect of Voids in Grouted Post-Tensioned Concrete Bridge Construction: Inspection and Repair Manual for External Tendons in Post-tensioned Bridges*, Texas Department of Transportation (TxDOT), Austin, TX.

TxDOT (2004), *Critical Evaluation and Condition Assessment of Post-Tensioned Bridges in Texas*, Texas Department of Transportation (TxDOT), Austin, TX.

VSL (2002), *Grouting of Post - Tensioning Tendons. Report Series 5*, VSL International Ltd., Lyssach, Switzerland.

Woodward, R.J. and Miller, E. (1990), "Grouting post-tensioned concrete bridges: the prevention of voids", *Highw. Transport.*, **37**(6), 9-17.