Detecting Grouting Quality in Post-Tensioned Prestressed Ducts with IE Method

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Keywords: Grouting Quality, Post-Tensioned Prestressed Ducts, Impact-Echo, Non-Destructive Evaluation.

Abstract: In post-tensioned prestressed bridges, the grouting quality of prestressed ducts is of paramount importance to the durability and load-bearing capacity of the bridge. Voids within the ducts may allow water and other corrosive substances to penetrate, leading to corrosion of the steel reinforcement and ultimately affecting the structural safety of the bridge. Impact-echo (IE) testing, an effective non-destructive evaluation (NDE) method, enables scientific and accurate assessment of the grouting quality of grouting ducts in pre-stressed structures without damaging the structure. This paper examines the impact-echo method for assessing grouting quality in post-tensioned prestressed ducts, confirming its adaptability and reliability for practical engineering applications.

1 INTRODUCTION

Prestressed concrete structures are widely used in civil engineering due to their superior mechanical properties and economic benefits (Sun et al., 2022). However, the grouting quality within prestressed ducts directly affects the protection of prestressing tendons and the long-term performance of the structures. Traditional testing methods have several limitations: they are often destructive, making the sample unusable and increasing costs, and usually assess only localized areas, missing overall conditions and latent issues. Furthermore, these methods depend on subjective human judgment, leading to variability and lack of precise real-time data, and are inadequate for detecting hidden internal defects. NDE technologies provide accurate and real-time inspection results without damaging materials or structures, improving safety and cost-effectiveness in industries like manufacturing and bridge maintenance. The IE method is a robust non-destructive evaluation technique, particularly valuable for assessing concrete structures. It enables comprehensive evaluations of internal elements critical for maintenance, safety, and longevity. This paper investigates the use of the IE method for assessing grouting quality in pre-stressed concrete pipelines (Hsieh and Lin, 2016).

2 THEORETICAL ANALYSIS

2.1 Theoretical Foundation: Reflections of Three Different Stress Waves

Impact-Echo (IE) is a non-destructive evaluation method for concrete and masonry structures, based on the generation and analysis of transient stress waves induced by an elastic impact (Cheng et al., 2021). The instantaneous disturbance (force or displacement) applied to the surface of a solid propagates internally in the form of three different stress waves: P-waves, S-waves, and R-waves. The direction of propagation of the P-wave is consistent with the direction of particle vibration, generating compressive or tensile stress. The S-wave propagates in a direction perpendicular to the particle vibration, resulting in shear stress. The R-wave propagates along the surface of the solid and is a type of inhomogeneous plane wave formed by the coupling of longitudinal and transverse waves. Among the stress waves generated by the impact, the P-wave and S-wave propagate into

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Liu, H., Xu and L.
Detecting Grouting Quality in Post-Tensioned Prestressed Ducts with IE Method.
DOI: 10.5220/0013591200004671
In *Proceedings of the 7th International Conference on Environmental Science and Civil Engineering (ICESCE 2024)*, pages 163-167
ISBN: 978-989-758-764-1; ISSN: 3051-701X

the interior of the solid as spherical wavefronts, while the R-wave radiates outward along the surface of the solid. The propagation modes of the three types of stress waves are shown in Figure 1.

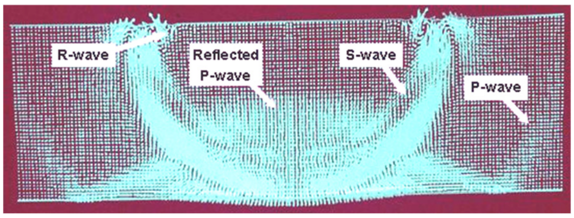


Figure 1: Finite element simulation of impact on a plate (Carino, 2001).

When a stress wave propagates through a material and encounters an interface with a different material, a portion of the incident wave is reflected. The amplitude of this reflected wave is dependent on the angle of incidence, achieving its maximum at 90° (normal incidence). Different types of stress waves can be clearly distinguished from one another, providing valuable information about the material properties. For instance, when the S-wave reaches the boundary at the bottom of the concrete slab, the reflected P-wave may have already arrived at the midpoint of the slab, highlighting the differing velocities of these wave types. As these waves interact with interfaces that possess varying acoustic impedances, they undergo complex phenomena such as reflection, refraction, and diffraction. These processes are critical for understanding the internal structure of the material being tested. Once the waves are captured by sensors, they undergo thorough analysis using spectrum analysis techniques. This involves transforming the time-domain signals into the frequency domain, which allows for the assessment of the relationship between the received signals and the quality of the concrete, thereby achieving the goal of NDE.

2.2 The Principle of IE Method

The principle of the IE method is that a brief mechanical impact, such as the strike of a small steel sphere on a concrete surface, generates low-frequency stress waves that travel through the structure and reflect off internal voids and external boundaries. The transducer near the impact point captures surface displacements from reflected waves. The recorded time-domain signals are transformed into the frequency domain to generate amplitude versus frequency spectra. When stress waves interact with the impact surface, voids, and external surfaces, they cause multiple reflections that result in transient resonances detectable in these spectra. These resonances are used to assess the structural integrity or locate voids within the structure. The principle of the IE method is illustrated (see Figure 2).

The IE method is capable of detecting voids in grouted prestressed ducts in various under a majority of circumstances. However, its performance is contingent upon several critical factors, including the geometric configuration of the structure, the dimensions and morphology of the voids, and the positioning and arrangement of the prestressed ducts. Furthermore, external environmental conditions, such as temperature fluctuations and humidity levels, can significantly influence the propagation characteristics of the stress waves and the accuracy of detection (Losanno et al., 2024; Dethof and Kessler, 2024; Tang, 2021).

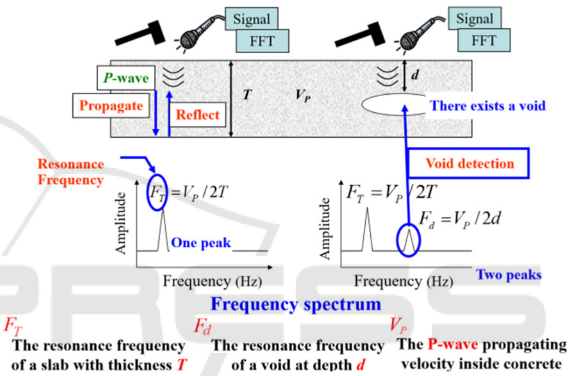


Figure 2: Principle diagram of IE method.

Similar to other defect types, voids within prestressed ducts may be positioned too deep in a structure to be detected. The IE signals recorded from intact concrete, completely grouted ducts, and partially grouted ducts will exhibit distinct patterns (JGJ/T 411-2017) (see Figure 3).

2.2.1 Normal Concrete

The principle is similar to that employed in the Impact-Echo method for detecting the thickness of concrete slabs. The tests produce distinctive waveforms and spectra, in which the prominent characteristics—especially the quantity and distribution of peaks—are clearly identifiable, as illustrated in Figure 3 (a). The relationship among the frequency peak (F_T), the compression wave velocity (V_P) and the echo depth (T) is expressed in the following equation:

$$F_T = \alpha_s \cdot V_p / 2T \tag{1}$$

Where α_s is a factor equal to 0.96 for a slab shape.

2.2.2 Fully Grouted Duct

Besides the frequency peak corresponding to the thickness, there is a higher frequency peak (F_{steel}) due to the existing of tendons as shown in Figure 3 (b). The reflection of the P-wave will occur from the tendons within the duct at a frequency of F_{steel} , which can be calculated:

$$F_{steel} = \alpha_s \cdot V_P / 4d_{steel} \tag{2}$$

Where d_{steel} is the distance from the impact point to steel tendons and V_P being the P-wave speed in concrete.

2.2.3 Not Fully Grouted Duct

The reflection from the backside is observed at a lower frequency than that from the shallower concrete/flaw interface (refer to Figure 3 (c)). In the presence of a void in the duct, the frequency measured will be:

$$F_{void} = \alpha_s \cdot V_P / 2d_{void} \tag{3}$$

Where d_{void} is the depth to the void.

When flaws exist in grouted prestressed ducts, the waveforms and spectra patterns, especially the spectra, are disrupted and modified. These alterations provide both qualitative and quantitative information regarding the presence and location of the flaws.

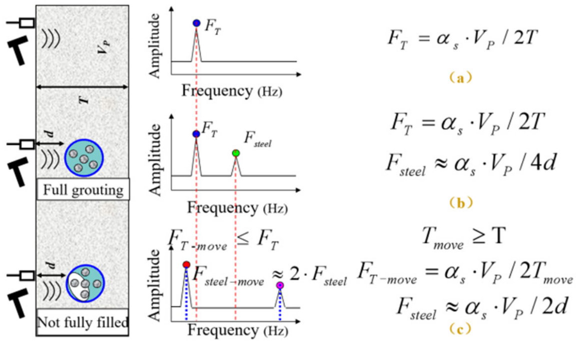


Figure 3: Impact response of different ducts.

In general, the IE method is favored for its simplicity and effectiveness, providing a straightforward approach to quickly and efficiently detect internal defects in materials and structures. It's non-destructive nature and ease of application make it an ideal choice for assessing the integrity of grouting quality in post-tensioned pre-stressed ducts without compromising their usability.

3 FIELD TEST AND CALCULATION OF THE EXPECTED FREQUENCY

The post-tensioned concrete bridge was a simply supported box beam bridge under construction, and IE method was employed to detect the grouting quality of the prestressed ducts on-site (see Figure 4).

The lateral ducts, with a cross section of 60×19 mm, were made of corrugated steel tubes. Each duct contained 3 steel tendons, each~15 mm in diameter. After the tendons were tensioned, the ducts were filled with expanded cement grout.

Figure 4: The IE method to detect the grout quality on site.

Testing parameters, including P-wave velocity and sampling frequency, should be determined before initiating a new test. The average P-wave velocity obtained from three measurements was 4050 m/s, with a sampling frequency of 60 kHz selected, yielding 1024 data points per record.

Reflection from the tendons:

For a depth of the steel tendons of 17 cm the expected frequency is:

$$f = C_P / 4d_{steel} = 4050\text{m/s} / (4\times17\text{cm}) = 5956 \text{ Hz}$$

Reflection from a void in the cable duct:

For a void depth of 14 cm within the duct, the expected frequency is:

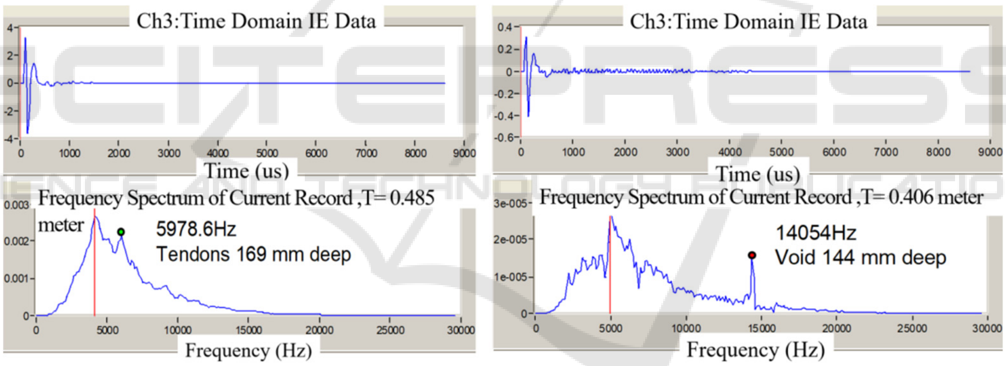
$$f = C_P / 2d_{void} = 4050\text{m/s} / (2\times14\text{cm}) = 14464 \text{ Hz}$$

4 RESULTS ANALYSIS

Two tendon ducts were selected for analysis: one that underwent successful injection without any discernible issues, and another suspected of containing voids due to difficulties encountered during the injection process.

The frequency spectrum of the fully grouted duct is presented in Figure 5 (a). Upon examination of this figure, a notable frequency peak at 5978.6 Hz is observed, which corresponds to a depth of 16.9 centimeters. This peak, in conjunction with the plate thickness frequency of 4576.1 Hz, representing the frequency of reflections arriving from the external surface, provides valuable insights. Importantly, the depth of 16.9 centimeters aligns precisely with the actual location of the tendons, which are situated within a range of 16 to 18 millimeters.

In Figure 5 (b), two prominent frequency peaks were observed. Notably, the plate thickness frequency registered at 4988.1 Hz, indicating a depth of 40.6cm. Yet, the intended thickness of the concrete structures beneath the impact point was 39cm, revealing the presence of voids in the tested area. This discrepancy stems from the extended propagation of P-waves, a clear indicator of cavities. Furthermore, theoretical frequencies for voids in the ducts at depths of 14cm and 18cm were predicted to be 14464 Hz and 11250 Hz respectively. Obviously, the detected frequency peak of 14054 Hz falls squarely within this range, confirming the presence of voids within the grouted tendon ducts.



(a) (b)

Figure 5: (a) Impact-echo frequency spectrum at the well-grouted section of cable duct. (b) The waveform and frequency spectrum of voided duct.

Figure 6: Un-grouted tendon duct.

Indeed, from Figure 6 authenticates these by showcasing the accurate representation of voids in un-grouted ducts.

5 CONCLUSIONS

Practical experience demonstrates that the impact-echo method is effective for detecting voids within grouted prestressed ducts in post-tensioned structures. A reliable assessment of internal grouting quality can be achieved through precise analysis of the IE signals.

The accuracy of the IE method for detecting post-tensioned prestressed ducts depends on factors such as P-wave velocity, the diameter of the steel spheres, and sampling frequency. Selecting appropriate testing parameters and employing a suitable mechanical impact to generate low-frequency stress waves are crucial for obtaining accurate results. However, in practical applications, the IE method may face limitations related to signal attenuation and data interpretation. To address these challenges, future research should focus on enhancing signal processing techniques, improving detection resolution, developing propagation models for complex structures, and advancing automated and multimodal detection systems. These efforts will expand the applicability and effectiveness of the impact-echo method in engineering practice.

Assessing the quality of grout injection in tendon ducts using non-destructive evaluation methods is an emerging area of study. In China, there are currently no ideal technologies or standards for this purpose. Extensive experimental research is required to calibrate the impact-echo testing method for assessing the internal grouting condition of prestressed ducts.

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