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ELASTIC WAVE PROPAGATION IN DIAGNOSTICS OF SELF-DRILLING SYSTEM OF GROUTED ANCHORS

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Abstract

The paper presents an experimental investigation of elastic wave propagation in a self-drilling hollow bar system, which is commonly used in geotechnical industry as the element of grouted ground anchors and soil nails. The single self-drilling hollow bar and self-drilling system of two bars connected by a coupler were considered. Longitudinal waves were excited at one end of the bar and registered at both ends, by means of PZT plate transducers. Additionally, in the case of connected bars, the transducer was also located at the coupler. The main aim of the study was to analyse the wave attenuation because of discontinuities in the form of mounting connections occurring along the bar length. The differences in wave propagation signals registered at single bar and the system of two bars were indicated and discussed.

Keywords: self-drilling system, grouted anchor, elastic wave propagation, non-destructive diagnostics

PROPAGACJA FAL SPRĘŻYSTYCH W DIAGNOSTYCE SYSTEMU SAMOWIERCĄCEGO KOTEW INIEKCYNYCH

Streszczenie

W artykule przedstawiono badania eksperymentalne dotyczące propagacji fal sprężystych w systemie samowiercącym, który jest powszechnie stosowany w przemyśle geotechnicznym jako element iniekcyjnych kotew i gwoździ gruntowych. Badaniu podlegał pojedynczy samowiercący pręt oraz dwa pręty połączone mufą. Fale podłużne były wzbudzane na jednym końcu pręta, a rejestrowane na obu końcach, za pomocą przetworników piezoelektrycznych. Dodatkowo, w przypadku systemu dwóch połączonych prętów, czujnik był umieszczony również na mufie. Głównym celem była analiza zaniku fali ze względu na nieciągłości w postaci połączeń montażowych pojawiających się na długości pręta. W pracy omówiono różnice w propagacji fal w pojedynczym pręcie oraz systemie złożonym z dwóch prętów.

Słowa kluczowe: system samowiercący, kotwa iniekcyjna, propagacja fal sprężystych, diagnostyka nieniszcząca

1. INTRODUCTION

In recent years, a lot of effort of scientists has been focused on developing effective diagnostics systems, which could be successfully used in industry. A special attention is paid to non-destructive techniques allowing for fast, low-cost and effective state assessment, especially of geotechnical facilities that cannot be inspected visually, because they are manufactured directly in the ground.

One of examples of geotechnical structures, which are commonly used as supporting elements of loose or collapsing soils, are grouted ground anchors and soil nails. Despite the fact that their structure is very similar, they can vary considerably in length. Much more problematic in the context of diagnosis are ground anchors, which length can reach even over a dozen meters. The scheme of the ground anchor is presented in Fig. 1. The main elements of the anchor are a bar and an anchor body, which is formed in the ground by the pressure injection of cement grout.

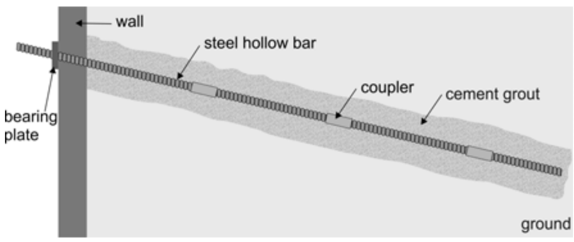


Fig. 1. Scheme of the anchor system

The real problem of such permanent structural elements is their durability, load capacity and compatibility of geometrical parameters with a project. Conventional diagnostics of grouted anchors and nails is mainly based on expensive and time-consuming destructive tests. Therefore nowadays various non-destructive techniques have been developed. One of very attractive and recently intensive investigated diagnostic methods is the technique based on the guided wave propagation phenomena. The idea of the use of elastic waves involves the excitation of vibration in a tested object and registration of signals in chosen places by special sensors. The analysis of the state of a tested structure often requires the processing of signals and appropriate interpretation of obtained results. Previous works indicate that elastic waves present a great potential in the condition assessment of ground anchors. Numerous studies concerns identification of free and bonding lengths of embedded bars based on wave propagation signals [11, 13, 14]. In [15] guided waves were used in the assessment of damage of adhesive bonding between a steel bar and concrete cover of two-layer cylindrical specimens. Different levels of delamination and its location were investigated. A non-destructive evaluation of pre-stress in metal tendons of ground anchors by means of elastic waves was presented in [1].

In most cases described in literature, the tendon of the anchor is considered as a prismatic steel bar with a constant shape of cross section and without any discontinuities occurring over the length. However, tendons of ground anchors and soil nails are often performed with the use of self-drilling hollow bars [16]. Those bars are characterized by left-hand thread for standard percussive drilling so the cross section varies through the bar length. The hollow cross-section allows for simultaneous drill and grout. Moreover, in the case of long anchors, the tendon is often performed as debonded bars with partially bonded couplers (Fig. 2). Then the length of the tendon can be easily adjusted to design assumptions by connecting appropriate number of bars.

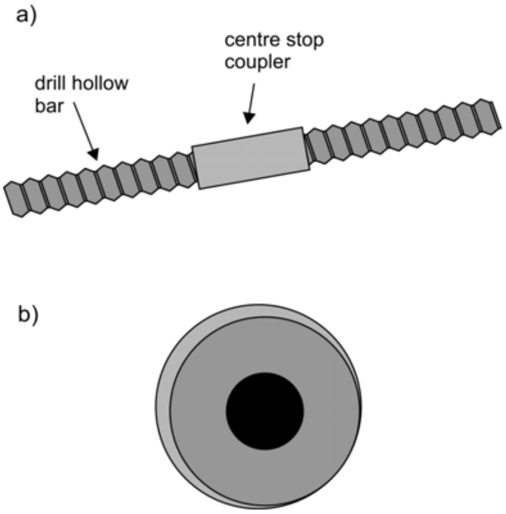


Fig. 2. Scheme of self-drilling systems of ground anchors: a) two drill hollow bars connected by the centre stop coupler; b) cross-section of the bar

The guided wave propagation becomes more complicated in drill hollow bars than in simple prismatic bars. Main factors influencing the phenomena of wave propagation are connected with the complex cross-section of the drill bar and the application of couplers. This paper presents results of experimental investigation of wave propagation in the drill hollow bar that is used for ground anchors and soil nails manufacturing. The single section of the bar and two sections connected by the coupler are investigated. The main aim of the study is to analyse how the wave is attenuated because of discontinuities in the form of mounting connections occurring over the bar length. The differences in wave propagation signals registered at single bar and the system of two bars were indicated and discussed.

2. DISPERSION CURVES FOR HOLLOW BAR

Waves excited in a hollow bar are dispersive waves. It means that the wave velocity and the number of propagating wave modes depend on the excitation frequency. The number of modes and their velocity for a given frequency can be graphically presented as so-called dispersion curves. They are a solution of a dispersive equation derived for the analysed type of an element (e.g. plate, multilayered bar, etc.). With the aim to obtain dispersion curves for the tendon of the anchor made with the use of self-drilling system, dispersive relations for the hollow bar need to be considered.

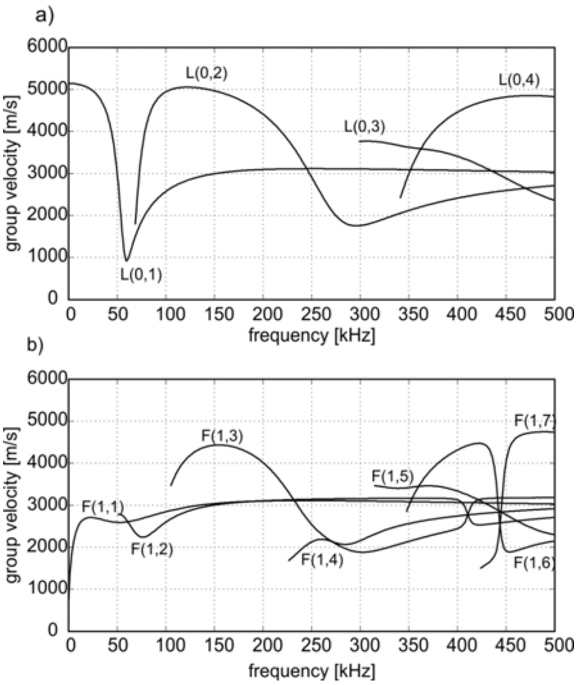


Fig. 3. Dispersion curves for steel hollow bar (E = 210 GPa, ν = 0.3, ρ = 7938.54 kg/m^3) with external diameter of 38 mm and internal diameter of 19 mm: a) longitudinal modes, b) flexural modes

The analysis of dispersive waves travelling in hollow bars has been investigated by many researchers. First exact solutions based on three-dimensional investigations for axially symmetric, nonaxially symmetric and torsional modes were derived by Gazis in 1959 [3, 4]; however, many earlier attempts of using shell theory approximations were made to solve this problem [2, 5-8, 10]. In general, dispersive curves cannot be obtained directly and mapping of branches requires extensive numerical computations. There is a possibility to use special programmes designed for prediction of properties of waves propagating in continuous structures with uniform cross-section. One of the code allowing solution of dispersion relations is DISPERSE [9]. In this paper, another free PC-DISP programme has been used for mapping dispersive curves [12].

The group velocity dispersion curves for both longitudinal and flexural modes are presented in Fig. 3. Since the self-drilling bar has a non-uniform cross section, the dispersion equation has been solved for the hollow bar with regular, smooth internal and external surfaces. The drill bar was considered as the pipe with the internal diameter equal to the diameter of the bar, while the external diameter was equal to the effective diameter of the drill bar. For this reason, the curves presented in Fig. 3 can be regarded only as an approximate solution giving coarse information about the number of wave modes and their velocities.

3. EXPERIMENTAL INVESTIGATIONS

3.1. Experimental model

The investigations were conducted on DYWI® Drill Hollow Bar System [16]. The first specimen was a single section of the self-drilling hollow bar R38-550 with a length of 1 m. Technical data for the bar has been taken from manufacturer [16]. The nominal thread diameter was equal to 38 mm, the effective external diameter was equal to 36.4 mm and the internal diameter was equal to 19 mm. The density of steel was equal to 7938.54 kg/m^3. The photographs of the drill hollow bar and its cross section are given in Fig. 4.

a)

b)

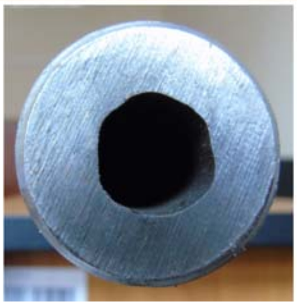


Fig. 4. Photograph of a) single self-drilling hollow bar and b) its cross section

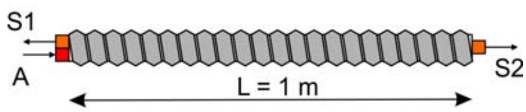
The second experimental model was the self-drilling system containing two R38-550 bars of equal lengths connected by the centre stop coupler (Fig. 5). The total length of the specimen was equal to 2 meters.

Fig. 5. Self-drilling hollow bar system connected by the centre stop coupler

3.2. Experimental equipment and localization of measurement points

The guided waves were excited and sensed by PZT plate transducers Noliac NAC2024. Waveforms were generated and registered by the device PAQ 16000D. An excitation signal was a ten-cycle sine function modulated by the Hanning window. The carrier frequency of 60 kHz was chosen on the basis of results of tuning test. For the chosen frequency wave signals were characterized by the highest value of the amplitude.

a)



b)

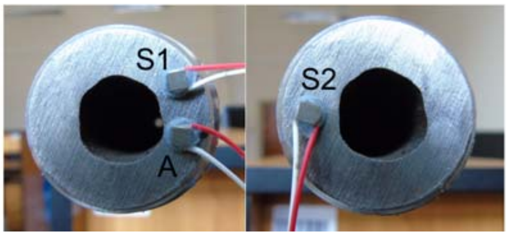


Fig. 6. PZT transducers at the single self-drilling hollow bar: a) configuration of actuator and sensors; b) detail showing actuator and sensors at the beginning and the end of the bar

The configuration of measurement points is given in Fig. 6 and Fig. 7, for the single bar and the bar system, respectively. In both cases, the waves were excited in longitudinal direction by the actuator attached to left end of the specimen. For the single self-drilling hollow bar, vibrations were registered by two PZT sensors, attached to both end of the bar (Fig. 6). In the case of the self-drilling hollow bar system three PZT sensors were used. Two sensors were attached at the both ends of the coupled bar to measure longitudinal waves and one additional sensor was attached to the surface of the coupler between bars to register vibrations perpendicular to the axis of the bar (Fig. 7).

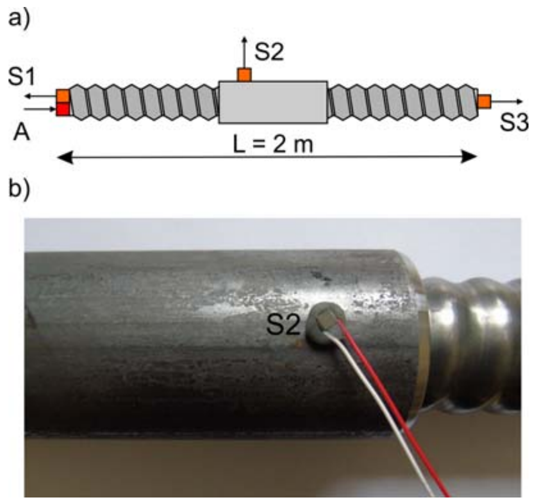


Fig. 7. PZT transducers at the self-drilling hollow bar system: a) configuration of actuator and sensors; b) detail showing sensor attached to the coupler

4. RESULTS

Wave propagation signals registered for the single self-drilling hollow bar are presented in Fig. 8. The first signal (Fig. 8a) was registered at the same end as the wave was excited (sensor S1), while the signal in Fig. 8b was registered at the opposite end (sensor S2).

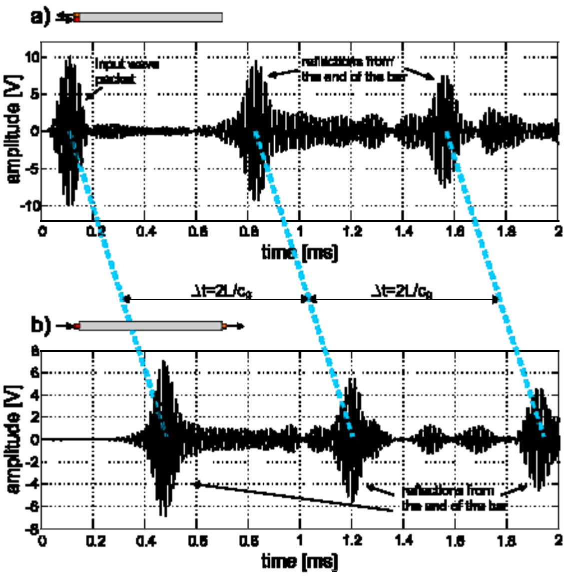


Fig. 8. Wave propagation signals registered at the single self-drilling hollow bar: a) signal registered at the beginning and b) at the end of the bar

In both signals, the input wave packet and wave packets corresponding to consecutive reflections from the ends of the bar can be identified. Particular reflections from the bar ends occurred at the same regular time intervals Δt and they are characterized by relatively higher value of the amplitude than other waveforms that can be observed in signals. These numerous additional low-amplitude peaks may be an outcome of a specific cress-section of the bar varying through its length. They can also be result of wave diffractions at the irregularities at the surface. Moreover, the actuator was not attached centrally. Non-perfect, eccentric actuator location may result in excitation not only longitudinal, but also flexural modes. For the chosen carrier frequency of 60 kHz, two additional flexural modes could be excited (compare Fig. 3b).

The experimentally determined group velocity of the longitudinal wave calculated based on the time of flight (2116.4 m/s) differs considerably from results obtained based on dispersion curves for a uniform hollow bar (1029 m/s). This discrepancy confirms that the dispersion curves calculated for a smooth hollow cylinder with dimensions corresponding to the dimensions of the considered self-drilling hollow bar do not reflect accurately the shape of curves for the real bar with thread.

The results for the self-drilling hollow bar system are illustrated in Fig. 9. Three signals were registered at the beginning of the bar (sensor S1), in the middle at the coupler (sensor S2) and at the end (sensor S3).

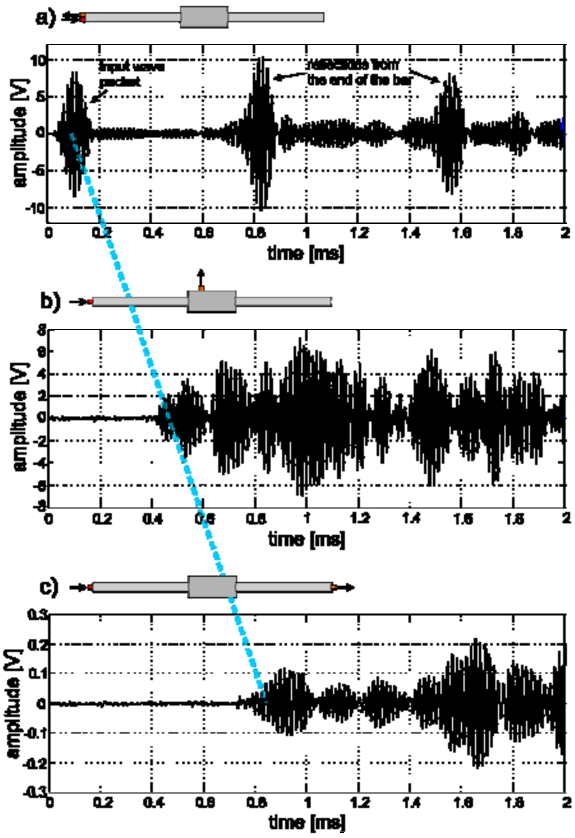


Fig. 9. Wave propagation signals registered at the self-drilling hollow bar system: a) signal registered at the beginning, b) at the coupler in the middle and c) at end of the bar

The straight line is drawn through the first registered wave packets. It can be seen that their registration time is proportional to the distance between the sensor and actuator. The angles of inclination of the lines for the single bar and the system of two bars do not differ so one can conclude that the presence of mounting connection has no influence on the wave propagation velocity.

The character of the signals differs considerable with the propagation distance. Only in the case of the first signal, particular peaks corresponding to reflections from the bar ends can be easily identified. In other two cases, the interpretation of signals is much more difficult and signals are characterized by numerous wave packets with the comparable value of the amplitude. Moreover, it can be seen that the amplitude values differ significantly between particular signals. The highest amplitude registered by sensor S1 was equal to 10 V, while for vibrations registered at the coupler (sensor S2) the amplitude did not exceed 8 V. The lowest amplitude characterized the signal registered at the end of the coupled bar system (sensor S3). The highest amplitude was equal to about 0.2 V and it was 50 times less than for the signal registered by sensor S1. Therefore, it can be observe that the wave was strongly attenuated when passing through the mounting connection of two bars, despite the fact that bars were highly tightened and there was no gap between them. The internal thread of the coupler was the same as threads of the bars, so the amplitude decrease was not a result of connection defect.

Finally, a comparison of signals registered by sensor S1 in both specimens is illustrated in Fig. 10. The signal for the single self-drilling hollow bar is plotted by grey line while for the self-drilling hollow bar system the signal envelope is plotted by black line.

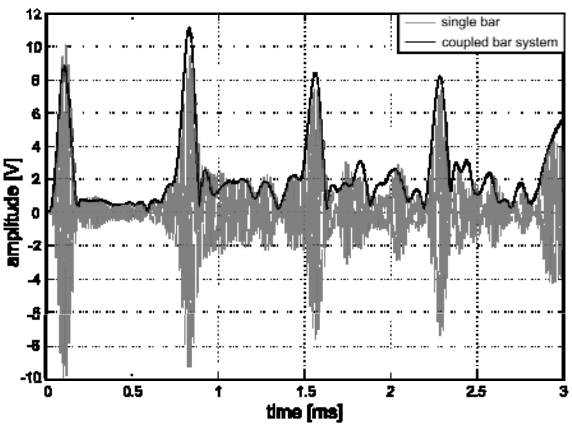


Fig. 10. Comparison of wave propagation signals registered by sensor S1 for the single self-drilling hollow bar and the self-drilling hollow bar system

It can be seen that there are no significant differences between signals, even in extended range of time up to 3 ms. The registration times of reflections from the end of the bar are similar and their amplitudes stay with good agreement. A high degree of similarity of these two signals registered for two different specimen lengths means that the large majority of the wave energy is reflected from the end of the first bar and it is not transferred from the coupler connection.

5. CONCLUSIONS

The paper presents experimental research of guided wave propagation in the self-drilling hollow bar system. Two types of specimens were investigated. Firstly, longitudinal waves were excited in the single hollow bar and then, in the system of two bars connected by the centre stop coupler.

The obtained results indicated that there was a discrepancy between the experimentally determined group velocity of the wave propagating in real hollow bar with thread and the group velocity determined based on dispersion curves for the pipe with external diameter equal to the nominal thread diameter. Therefore, such dispersion curves can be considered only as approximate solution in the assessment of wave velocity in thread bars.

The comparison of wave propagation signals and the time-of-flights of particular reflections in both specimens has brought a conclusion that the mounting connection between the bars did not influence the wave propagation velocity. However, the connection influenced greatly the character of the signals. Signals registered at the both ends of the single bar appeared easy to interpret. Particular reflections had relatively high amplitudes and they could be clearly indicated. In contrast, signals registered at the coupler and at the end of the coupled bar system were characterized by numerous low-amplitude packets with the comparable value of the amplitude.

The most important conclusion concerns the wave attenuation caused by the discontinuity in the form of the mounting connection. The signal registered at the end of the bar system had over 50 times lower amplitude than the signal registered near actuator. Despite the fact that bars were highly tightened and there was no gap between them, the wave was strongly attenuated when passing through the connection of two bars. The comparison of two signals registered by sensor attached at the beginning of the bar for the single bar and the system of coupled bars confirmed that the large majority of the wave energy was reflected from the end of the first bar and it was not transferred from the coupler connection.

The presented results indicated that strong wave dissipation at the bar connection need to be taken into account in designing of structural health monitoring systems dedicated for real geotechnical facilities, like ground anchors or soil nails, constructed with the use of the self-drilling hollow bar system.

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