ELIMINATION OF THE RAYLEIGH WAVE EFFECT ON LOW STRAIN INTEGRITY TEST RESULTS

(Part 1: Experimental Investigation)

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ABSTRACT

The presence of Rayleigh waves reflecting back and forth along the surface of the pile top under an impact blow results in location-dependent velocity responses during low strain integrity tests. There have been no reported studies on the behaviour of reflected Rayleigh waves at vertical free end boundaries, which have similar boundary conditions to a pile top. Since there has been no analytical description of this behaviour reported, there clearly needs to be an experimental investigation into the behaviour of reflected Rayleigh waves. This paper describes an experimental approach used to investigate the behaviour of Rayleigh waves. It was found that there is a correlation between the horizontal velocity and vertical velocity component of Rayleigh waves.

Keywords: surface waves, Rayleigh waves, sonic echo method, integrity testing

1. INTRODUCTION

In 1885, Lord Rayleigh demonstrated theoretically that waves are able to propagate over the plane boundary between an elastic half space and a vacuum, with the amplitude of the waves decaying exponentially with depth. These waves were named after Lord Rayleigh or surface waves. An impact on a surface generates Rayleigh waves which propagate along the surface. These waves are reflected by internal interfaces or external boundaries. According to Sansalone and Carino (1986), when an accelerometer is attached close to the impact, the dominant waves are compression and Rayleigh waves. However, the main objective of sonic echo testing is to measure the response due to compression waves only. The presence of Rayleigh waves reflecting back and forth along the surface of the pile top is a major concern because Rayleigh waves introduce background noises to the results and hence confuses the interpretation of results. For this reason, it causes the velocity responses to vary depending on the locations of the hammer impact and the accelerometer. Hence, there is a need to have a technique to obtain a location-independent response in order to interpret velocity responses reliably.

There have been various experimental and analytical studies done on the reflection and transmission of Rayleigh waves in the past forty years. Bremaecker(1958) used an experimental approach to investigate the transmission and reflection of Rayleigh waves upon arrival at a corner with angle varying from 0° to 180°. However, Lapwood(1961) explored the situation analytically, considering only the transmission on Rayleigh waves. In another independent experimental and theoretical study, Hudson and Knopoff (1964a,1964b) examined the transmission and reflection of Rayleigh waves at a corner of a homogenous elastic wedge.

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Although there has been extensive work done on transmission and reflection of Rayleigh waves, no study had been reported on the behaviour of reflected Rayleigh waves at vertical free end boundaries which have similar boundary conditions to a pile top. Therefore, behaviour of Rayleigh waves upon a reflection from a free end boundary is not known. Unfortunately, it is due to the reflected Rayleigh waves generated during integrity testing on pile top that had been making results interpretations difficult. Since there has been no analytical description of this behaviour reported, there clearly needs to be a detailed investigation into the behaviour of reflected Rayleigh waves.

This paper describes an experimental approach used to investigate the behaviour of Rayleigh waves in the velocity responses and hence to propose a method to eliminate the Rayleigh wave effect.

2. EXPERIMENTAL TESTING PROGRAM

The aims of the experiments are to investigate the behaviour of Rayleigh waves upon reflection from a free end vertical boundary and to ascertain whether a relationship exists between the horizontal velocity and vertical velocity of Rayleigh waves. Experiments were carried out under a vertical free end boundary condition to emulate the behaviour of Rayleigh waves travelling along a pile top. An impact to an elastic solid generates compression, shear and surface waves (Sansalone, Lin et al.,1997). In order to study the response due to Rayleigh waves only, compression and shear waves needed to be isolated from Rayleigh waves. In an elastic half space, compression and shear waves decay with distance as $1/r$ (where r is distance from the source of impact) (Wesley,1973) while Rayleigh waves decay with distance as $1/\sqrt{r}$ (Viktorov,1967). Hence, compression and shear waves attenuate at a faster rate than Rayleigh waves. Therefore measurements of horizontal and vertical components of Rayleigh waves were taken at a sufficient distance away from the point of impact to isolate both compression waves and shear waves.

2.1 Testing Procedure

The experiments were performed upon piles with different lengths using hammers of different sizes. The specifications of the piles are shown in Table 1. Ideally the pile length was as long as possible to ensure the isolation of compression waves and shear waves when measurements of Rayleigh waves were taken. However, only a maximum pile length of 12 m was obtained.

Simultaneous measurements of horizontal and vertical velocities were taken at various distances away from the hammer impact (see Table 2) as shown in Figure 1. In order to identify the time at which reflected Rayleigh waves arrived in the velocity response, the wavespeed of Rayleigh waves needed to be determined. Therefore, two accelerometers were attached at two different distances to measure the vertical velocities so that incident Rayleigh waves could be identified in the velocity responses (see Figure 2). Having identified the times at which incident Rayleigh waves arrived in the two velocity responses, the wavespeed of Rayleigh waves was then determined.

Table 1: Pile information

Pile Number	Length(m)	Age	28 days strength (MPa)	Condition
8474	12	11 days	44	1
4552	14.77	8 months	74.5	1

Table 2: Summary table of testing program

Case	Location of Impact from edge(m)	L''(m)	Dv_1(m)	Dv_2(m)	Pile Number	
					8474	4552
1	0	4			•	
2	0	5				•
3	0	6			•	
4	0	7				•
5	0	8			•	
6	0	9				•
7	0	10			•	
8	0	11				•
9			0	4	•	
10			0	5		•
11			0	6	•	
12			0	7		•
13			0	8	•	
14			4	10	•	
15			5	9		•
16			5	11		•

- Small hammer

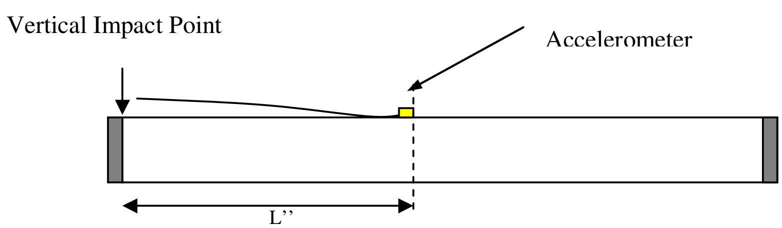


Figure 1: Measurement of simultaneous horizontal-vertical velocities

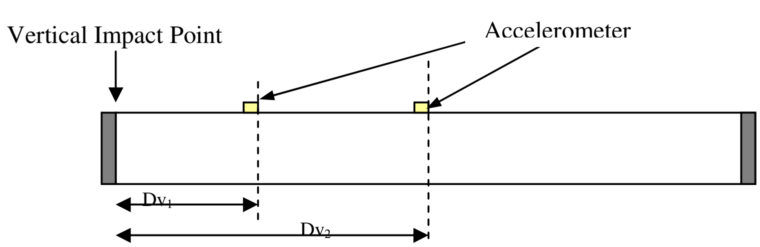


Figure 2: Measurement of vertical velocity

2.2 Determination of wavespeed of Rayleigh waves

As suggested by Sansalone, Lin et al.(1997) the arrival of Rayleigh waves was identified as a small vertical displacement before an initial large drop in the displacement signal. Figure 3 shows the arrival of compression waves, *P*, and Rayleigh waves, *R,* in a typical displacement signal where the impact was located 0.15 m from the receiver.

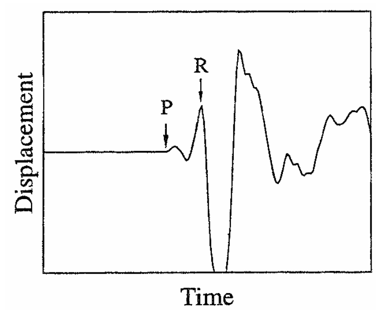
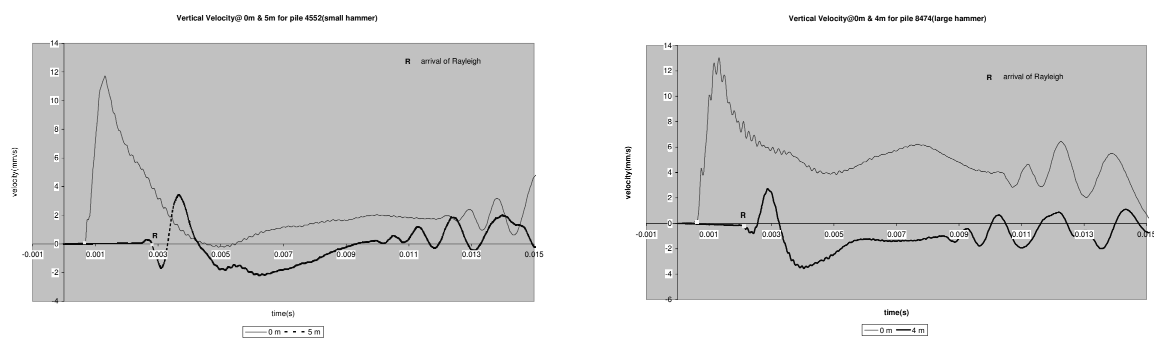


Figure 3: Displacement signal for test performed at distance 0.15 m (Sansalone, Lin et al.,1997)

A small vertical displacement before an initial drop in the displacement signal is equivalent to zero velocity followed by negative velocities in the vertical velocity signal. Therefore, the arrival time of incident Rayleigh waves can be identified directly in the vertical velocity response.

The velocity response of pile 8474 for case 10 and the velocity response of pile 4552 for case 11 are presented to demonstrate the identification of arrival of incident Rayleigh waves. The arrival times of incident Rayleigh waves were tagged in the vertical velocity responses as shown in Figure 4. Using these times, the wavespeed of Rayleigh waves could then be determined since the distance between the two accelerometers was known.



(a) (b)

Figure 4: Identification of arrival of incident Rayleigh waves in (a) pile 4552 (b) pile 8474

2.3 Identification of the arrival times of incident and reflected Rayleigh waves

In the horizontal-vertical velocity responses, the arrival times of incident Rayleigh waves were identified using a similar technique as that used to determine the wavespeed of Rayleigh waves. Having determined the experimental wavespeed of Rayleigh waves, the arrival times of reflected Rayleigh waves were subsequently calculated using the following equations:

$$T_1 = T_0 + \frac{2.L}{c_r} \qquad \text{Equation 1} \qquad\qquad T_2 = T_1 + \frac{2.L''}{c_r} \qquad \text{Equation 2}$$

where T_0 = arrival time of incident Rayleigh waves

T_1 = arrival time of first reflection of Rayleigh waves

T_2 = arrival time of second reflection of Rayleigh waves

c_r = wavespeed of Rayleigh waves

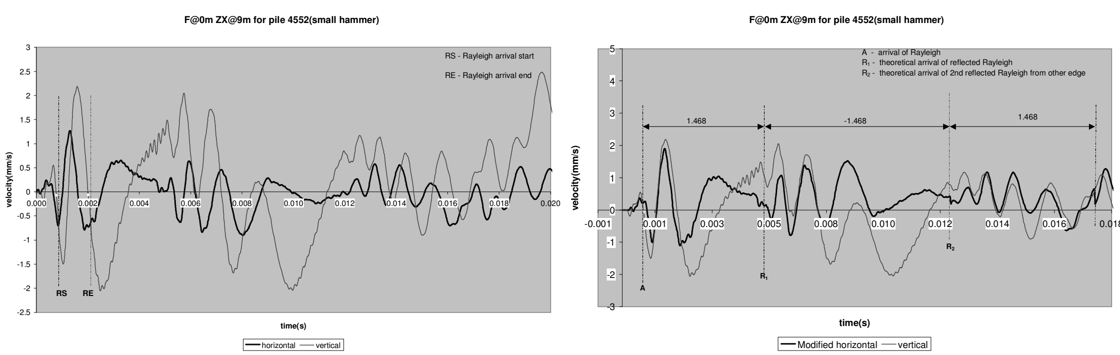
L and L" = the distances as defined in Figure 1

2.4 Analysis of horizontal-vertical velocity responses

After identifying the times at which Rayleigh waves arrived and reflected from the boundary, the correlation between the horizontal and vertical velocity upon arrival and reflection from the free end boundary was investigated to establish whether it was possible to deduce vertical velocity from the measurement of horizontal velocity.

According to Kolsky(1963), the path of any particle is an ellipse and its major axis is normal to the surface. For particles at the surface (z = 0), the ratio between the major and minor axes of the ellipse is 1.468. This suggests that the ratio of the maximum amplitude of vertical velocity to horizontal velocity component of Rayleigh waves should be 1.468. Therefore, a correction factor of 1.468 was applied on the measured horizontal velocity response to assess the validity of this ratio. An appropriate time phase delay was also applied to ensure that both horizontal and vertical velocity responses were in phase.

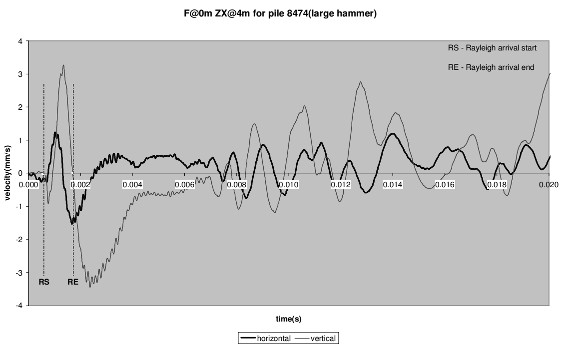
To illustrate the relationship between the corrected horizontal velocity and vertical velocity, the velocity responses of case 1 for pile 8474 and case 6 for pile 4552 are presented. Figures 5 and 6 show the horizontal-vertical velocity responses before and after a correction factor of 1.468 was applied. It was found that a reversal sign is required at the time at which Rayleigh waves reflected upon the vertical free end boundary.



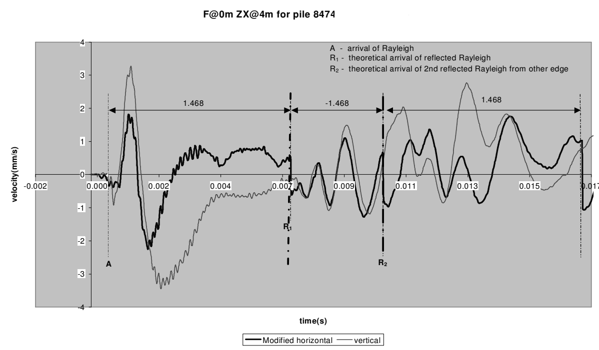
(a) (b)

Figure 5: Velocity response of pile 4552 (a) before (b) after correction factor is applied

As revealed by the graphs in Figure 5, the 'corrected' horizontal velocity response was found to match quite well in phase and amplitude with the vertical velocity response at the arrival time of incident Rayleigh waves. The 'corrected' horizontal velocity response was generally in phase with the vertical velocity of Rayleigh waves despite a small difference in the amplitude at the time, R_1, when Rayleigh waves reflected from the vertical free end boundary. The ‘corrected’ horizontal velocity response was in phase with the vertical velocity and matched fairly well with the vertical velocity response at the time when Rayleigh waves reflected from the other boundary, R_2.



(a)



(b)

Figure 6: Velocity response of pile 8474 (a) before (b) after correction factor is applied

As revealed by the graphs in Figure 6, the ‘corrected’ horizontal velocity response was found to match well in phase with the vertical velocity response at the arrival time of incident Rayleigh waves despite a small difference in the amplitude. The ‘corrected’ horizontal velocity response was also found to match well with the vertical velocity response at the time,R_1, when Rayleigh waves reflected from the vertical free end boundary.

For the case where there is a difference in the amplitude of the ‘corrected’ horizontal velocity and the vertical velocity, it is likely that there was interference from the unwanted waves, in this case compression waves. An appropriate correction factor is needed to improve the correlation between the two velocities. The difference in the amplitude could be due to the distance between the accelerometer and the hammer impact being insufficient to obtain a pure Rayleigh response. The difference in the amplitude could also due to inconsistency in the accelerometer attachment. The accelerometer had to be attached with the same pressure at all places for the measurement of amplitude to be significant. In this experiment, it was not practically possible to achieve this ideal condition.

Despite a small difference in the amplitude of ‘corrected’ horizontal velocity and vertical velocity, the results have shown that with appropriate correction factor, it is possible to deduce the vertical velocity component of Rayleigh waves from the measurements of the horizontal velocity of Rayleigh waves.

3. CONCLUSION

Some understanding on the behaviour of Rayleigh waves reflecting back and forth along the pile top was achieved based on the experimental work done. Through the analysis, it was demonstrated that the horizontal velocity could be used to deduce the vertical velocity of Rayleigh waves despite the difference in the amplitude of the ‘corrected’ horizontal and the vertical velocity in the reflected Rayleigh waves. The reasons for the difference were discussed in section 2.4. It was also found that the sign of the correction factor changes when Rayleigh waves reflected from the vertical free end boundary.

A technique was subsequently developed to enable the elimination of the vertical velocity of Rayleigh waves from the vertical velocity responses. The key aspect of the technique is the simultaneous measurements of the horizontal and vertical velocities during low strain integrity testing. By measuring the horizontal velocity of Rayleigh waves, the vertical velocity of Rayleigh waves could be deduced by applying an appropriate factor and subsequently be eliminated from the vertical velocity responses. The implementation of the technique is not discussed in this paper.

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