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Effect of Void Ratio of Concrete on Evaluation of P-wave Velocity by Impact-echo Method

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Abstract: There are many causes such as casting, loading, high temperature, etc., that may increase the void ratio or crack of concrete and thus affect its quality. Evaluating the quality of concrete based on the measured values of internal P-wave velocity is commonly used in concrete engineering. Impact-echo method is one of the famous nondestructive methods to measure P-wave velocity for concrete. In this study, commercial software of finite element analysis, LS-DYNA, is used to simulate the transient analysis of a concrete slab of $200 \times 1000 \times 1000$ mm subjected to an impact loading using the 2-D axisymmetric elements. The variables of concrete property in the numerical analysis include three different dynamic moduli of elasticity (20, 30 and 40 GPa) and three void ratios (0, 10 and 20 %). Numerical results show that, in average, the P-wave velocity of concrete slab decreases in the range of 11.80-11.93 % and 25.70-29.28 % with void ratio of 10 % and 20 %, respectively, for all three dynamic moduli of elasticity.

Keywords: Impact-echo; nondestructive method; LS-DYNA transient analysis; void; concrete.

1. Introduction

Concrete is one of the most commonly used construction materials in construction engineering. Many causes such as casting, loading, high temperature, etc., may increase the void ratio or crack of concrete that thus affects significantly its quality and performance. However, the effects of void on the response of concrete material is usually ignored in numerical analysis.

In order to evaluate the changes of concrete quality, many nondestructive evaluation method are used in concrete engineering. The nondestructive evaluation methods (e.g.. ultrasonic pulse velocity testing, convenient impulse response method and Impact-echo method) based on the measured values of internal P-wave velocity are commonly used.

For homogeneous, semi-infinite and elastic solids, the P-wave velocity, $C_{P,th}$, is function of dynamic elastic modulus, E_d, the bulk density, ρ, and Poisson's ratio, υ. The relationship for these four material properties is determined by the following equation:

$$C_{P,th} = \sqrt{\frac{E_d(1-\upsilon)}{\rho(1+\nu)(1-2\upsilon)}} \tag{1}$$

For normal concrete, the P-wave velocity varies from 3000 to 5000 m/s [1] and the dy-

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namic elastic modulus of normal concrete is ranging from of 20 to 40 GPa [2].

Impact-echo method is one of the famous nondestructive methods that is not only used to measure P-wave velocity for concrete but also used to estimate the thickness of concrete slab, according to ASTM C1383 [3]. The equipment setup of impact-echo method for measuring P-wave velocity is schematically shown in Figure 1. The typical signal of transducer 1 and 2 [4] are shown as Figure 2. The velocity of P-wave, C_P, is determined as following:

$$C_P = \frac{L}{\Delta t} = \frac{L}{t_{P2} - t_{P1}} \tag{2}$$

where, L= the distance between the transducers= 300 mm, t_{P1} = the arrival time of P-wave at transducer 1, t_{P2} = the arrival time of P-wave at transducer 2.

Thus, in order to investigate the effects of internal voids on the behavior of concrete, in this study, the impact-echo method is used for measuring P-wave velocity in a numerical simulation that conducts the transient analysis for a concrete slab of various voids with the commercial software of finite element analysis, LS-DYNA. The details of numerical simulation program will be given at following sections.

2. Numerical simulation program

The software of LS-DYNA is used as the numerical simulation analysis tool in this study. The geometry of FEM model is a 200 mm thick circular disk with diameter of 2000 mm. The element type of LS-DYNA is determined as 2D axial symmetry (2D solid 162) in order to reduce the reflection effect from the boundary.

In addition, the mesh size of each element is chosen as 0.25×0.25 mm The simulation of the y-axis displacement of a concrete slab impacted by a transient force is analyzed by the LS-DYNA. The function of transient force is determined as following [5]:

$$P(t) = \sin^{1.5}\left(\frac{t}{t_c}\pi\right) \tag{3}$$

where t_c is duration (or contact time) of impacts between small steel spheres and concrete surface. Sansalone and Streett [1] suggested that the range of contact time is 15-100μs. In this study, t_c is chosen as 30 μs and the maximum load is chosen as 7500 N simulating a half-sine-shape transient force as shown in Figure 3. The transducer 1 and 2 are set at a distance of 150 and 450 mm, respectively, to the impact source at center of the circular disk in order to obtain y-axis displacement responses. Furthermore, the data quantities are chosen as 2048 and the time step is 0.667μs in this study.

The variables of concrete property in the numerical analysis include three different dynamic moduli of elasticity (20, 30 and 40 GPa) and three void ratios (0, 10 and 20 %) in this study. The properties of concrete material and void (air) are shown as Table 1. On the other hand, five separate models with each void ratio were randomly distributed by computer program which was written with FORTRAN computer language, respectively. The typical models of concrete slab with different void ratio are shown as Figure 3.

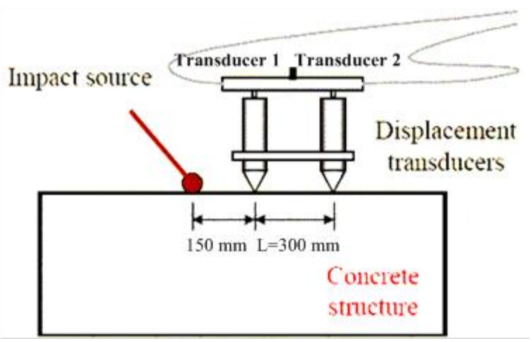
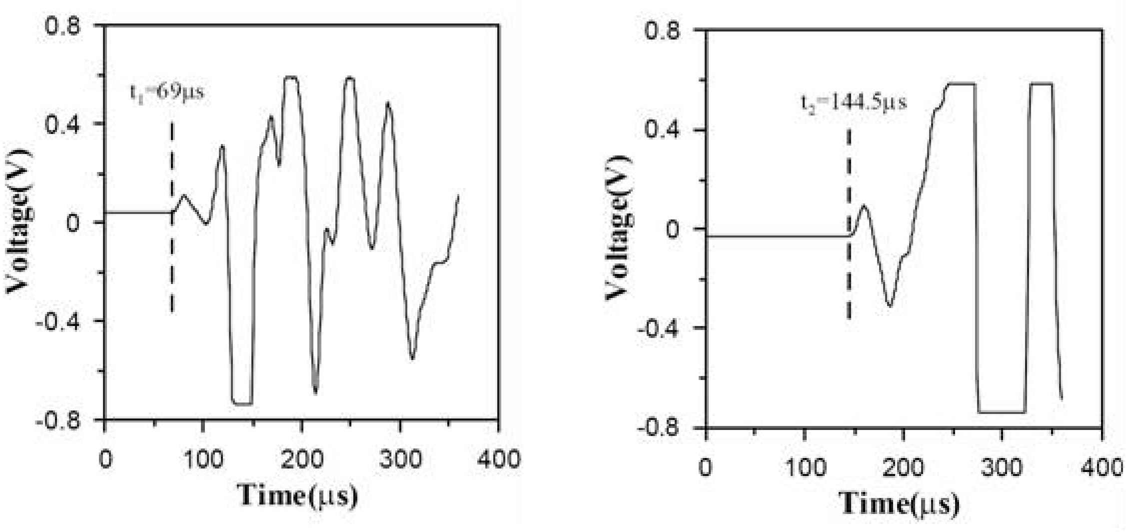


Figure 1. Equipment setup of Impact-echo method [1]



(a) transducer 1 (b) transducer 2

Figure 2. Typical signal of Impact-echo method [4]

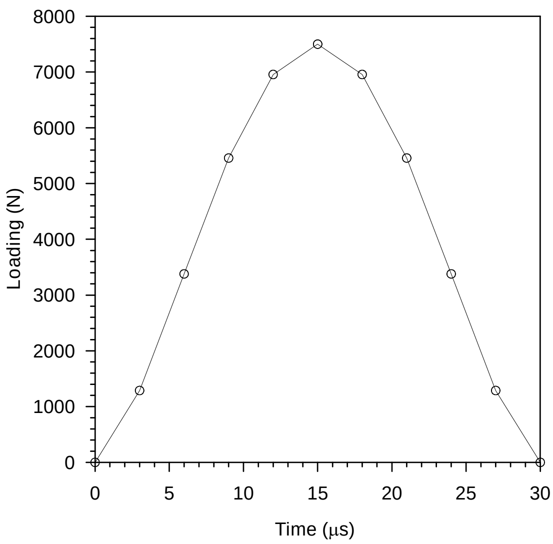


Figure 3. Transient force curve

Table 1. Properties of material for numerical simulation

	E_d (GPa)	Bulk density (kg/m^3)	Poisson's ratio
concrete	20, 30, 40	2400	0.18
void (air)	1×10^{-11}	1.3	0.1

3. Result and discussion

The theoretical P-wave velocities ($C_{p,th}$) calculated by equation (1) are 3008, 3684 and 4254 m/s with dynamic modulus of 20, 30 and 40 GPa, respectively. The results of numerical simulation analysis are shown as Table 2, 3 and 4. It shows that the average P-wave velocities of concrete with 0 % void ratio are 2920, 3575 and 4100 m/s, respectively, for the dynamic modulus of 20, 30, 40 GPa. The deviations of -2.93, -2.96, -3.62% between $C_{p,th}$ and C_p are less than 5%, respectively. Thus, the numerical model for the evaluation of C_p is feasible in this research. On the other hand, they also present that the average P-wave velocity of concrete decreases with the increase of void ratio. The relationship between C_p and $C_{P,th}$ with different void ratio of concrete is shown in Figure 5 and can be expressed by the following equations through curve fitting technique:

$$C_P = 0.841 C_{P,th} + 132.804 \text{ For void ratio} = 10\% \quad (4)$$

$$C_P = 0.748 C_{P,th} + 88.226 \text{ For void ratio} = 20\% \quad (5)$$

In order to know the effect of void ratio of concrete on evaluation of P-wave velocity, we define the equation of decrease ratio of P-wave velocity as following:

$$\text{Decreaseratio of CP(\%)} = \frac{(C_P - C_{P,th})}{C_{P,th}} \times 100\% \quad (6)$$

Figure 6 shows that the decrease ratio of P-wave velocity is in the range of 11.80-11.93 % and 25.70-29.28 % with void ratio of 10 % and 20 %, respectively. The effect of dynamic elastic modulus on the decrease ratio of P-wave velocity is not significant.

Table 2. Result of numerical simulation (E_d=20 GPa， $\rho = 2400$ kg/m^3，υ=0.18)

Void ratio (%)	No	t_{P1} (μs)	t_{P2} (μs)	C_P (m/s)	$C_{p,ave}$	Standard Deviation (m/s)
0	1	50.35	153.10	2920	2920	–
10	1	54.51	170.54	2586	2662	41
	2	55.69	167.49	2683		
	3	59.92	171.62	2686		
	4	58.13	169.17	2702		
	5	55.68	168.77	2653		
20	1	65.25	202.66	2183	2172	80
	2	63.70	210.63	2042		
	3	66.43	199.70	2251		
	4	67.80	200.83	2255		
	5	59.99	201.02	2127		

Note: $C_{P,th}$ (m/s)= 3008 m/s (calculated by equation (1))

Table 3. Result of numerical simulation (E_d=30 GPa， $\rho = 2400$ kg/m^3，υ=0.18)

Void ratio (%)	No	t_{P1} (μs)	t_{P2} (μs)	C_P (m/s)	$C_{p,ave}$	Standard Deviation (m/s)
0	1	42.45	126.36	3575	3575	—
10	1	45.31	139.52	3184	3229	30
	2	46.32	139.94	3204		
	3	50.46	142.31	3266		
	4	48.93	141.37	3245		
	5	47.46	139.87	3246		
20	1	53.24	166.46	2650	2649	84
	2	55.95	169.12	2651		
	3	55.67	175.87	2496		
	4	56.00	166.66	2711		
	5	57.15	166.75	2737		

Note: $C_{P,th}$ (m/s)= 3684 m/s (calculated by equation (1))

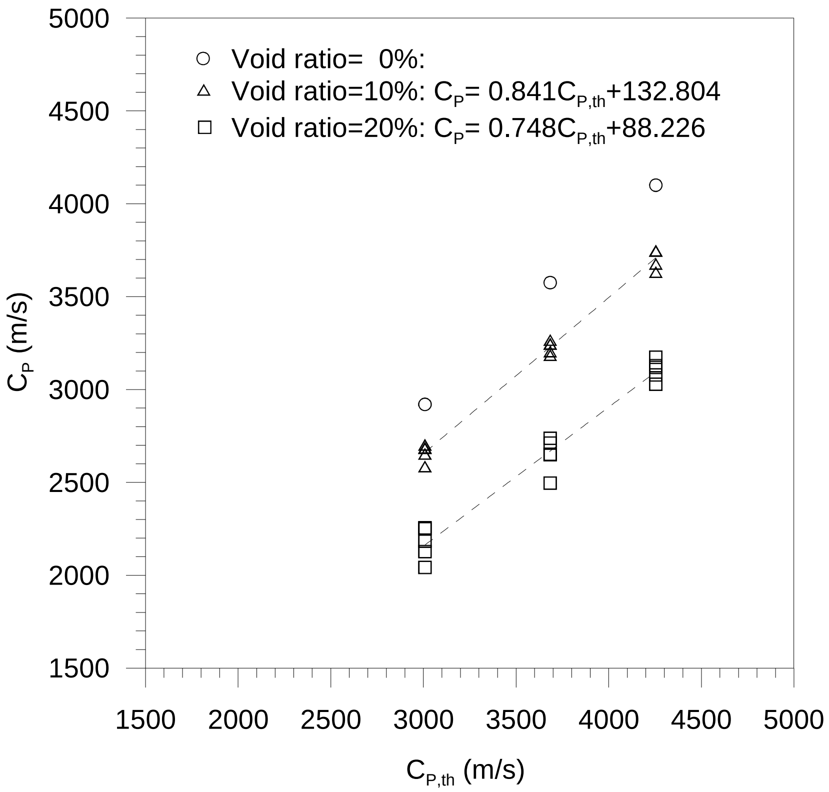


Figure 5. Typical model of concrete slab with various void ratio

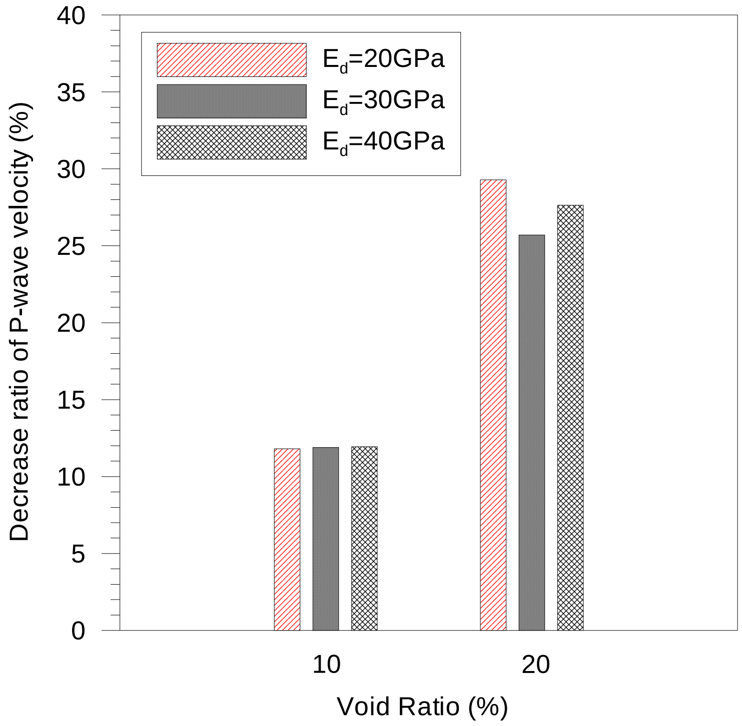


Figure 6. Relatioship of DecreaseTypical model of concrete slab with various void ratio

4. Conclusions

From the results of numerical simulation and discussion in this study, the following conclusions can be drawn:

1. The results of the numerical experiment in this study verify the phenomena that P-wave velocity of concrete has a strong inverse dependency on the void ratio, ie., the decrease ratio of P-wave velocity is in the range of 11.80-11.93 % and 25.70-29.28 % with void ratio of 10 % and 20 %, respectively.
2. For concrete element with fixed values of Poisson's ratio of 0.18, density of 2400 kg/m^3 and constant void ratio or 10% or 20%, the effects of dynamic moduli of elasticity varied from 20 to 40 GPa on the P-wave velocities are insignificant.

5. Acknowledgements

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