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Abstract This study aims to verify a method for accurately estimating the sizes of the column, slab, and beam members of concrete structures using the impact echo method, which is a nondestructive testing method. The concrete specimens are designed and fabricated with six single-layer frame specimens composed of columns, slabs, and beam members based on three strengths of 24, 30, and 40 MPa. To estimate the sizes of the members according to the member types of concrete structures, the experiment was performed using the impact echo method. As a result of estimating the sizes of the concrete column members using the impact echo method, the error rate is 2.9%. As a result of estimating the depth of the concrete beam members, the error rate is 9.7%. And, as a result of estimating the thickness of the concrete slab members, the error rate is 2.4%. These results confirmed that quality control of the members of concrete structures is possible by estimating their sizes using a non-destructive testing method.

Keywords: size, estimation, concrete structures, impact echo method, nondestructive test

1. INTRODUCTION

Building accidents, such as tilting, deformation, and collapse, frequently occur. To prevent such accidents, it is extremely important to establish a non-destructive testing method for accurately estimating the member size of buildings for safety diagnosis of buildings and to comply with standards related to building precision safety diagnosis or non-destructive testing according to the situation. Studies that have applied non-destructive testing to concrete structures composed of members, such as columns, walls, slabs, and beams, are limited. One of the major challenges when safety diagnosis is conducted for the maintenance of existing buildings is the lack of design drawings. As there are more cases where the measurement of the member size is not possible owing to multiple reasons than cases where the member size can be measured without any interference, such as from finishing materials, the establishment of a method for accurately estimating the member size of buildings using non-destructive testing is urgently needed.

This study, therefore, aims to propose a method for accurately estimating the sizes of the column, slab, and beam members of concrete structures using the impact echo method, which is a non-destructive testing method. The proposed method will contribute to the quality control of members by allowing for a more accurate estimation of the sizes of the column, slab, and beam members of existing structures. As for the concrete specimens, six single-story frame specimens composed of column, slab, and beam members in different sizes were fabricated for the designed strengths of 24, 30, and 40 MPa. To estimate the sizes of the members according to the member types of concrete structures, the experiment was performed using the impact echo method in accordance with ASTM C 1384-04. Based on this, a method of evaluating the member size estimation for concrete structures was established.

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2. LITERATURE REVIEW

In the 1980s, an evaluation report on ACI 228 non-destructive testing with 38 papers on the standards of non-destructive evaluation and measurement area was published in the United States (ACI (2013)). Based on this report, many studies have been conducted on applying non-destructive testing to the diagnosis of concrete structures (T. Epp, D. Svecova & Y. J. Cha (2018); H. Azari & S. Lin (2019)). The representative previous studies on the impact echo method are as follows.

In 2017, Liu et al. identified that the echoes from cracks and rebars can be distinguished through impact-echo phase analysis (P. L. Liu, L. C. Lin, Y. Y. Hsu, C. Y. Yeh, & Yeh, P. L. (2017)). Kang et al. conducted research on the detection of cavities around concrete sewage pipelines using the impact echo method (J. M. Kang, S. M. Song, D. H. Park, & Choi, C. H. (2017). In 2015, Oskar Baggens and Nils Ryden conducted research on the near field effects of impact echo method tests and found that the near field effects cause an error that underestimates the thickness (Oskar Baggens, Nils Ryden, (2015). In 2013, Xiaobin Lu et al. conducted research on obtaining the dynamic modulus of elasticity using the impact echo method (Xiaobin Lu, Qichen Sun, Wei Feng & Juntao Tian. (2013)). In 2007, Kim et al. conducted research on estimating the compressive strength and flaw of concrete slabs using the impact echo method and the spectral analysis of surface waves (S. B. Kim, S. U. Hong, & Y. S. Cho, (2007)). However, most of these studies were conducted using a mock-up, and studies on the quality control of the members of structures are limited (S. U. Hong and Y. S. Cho, (2006)). Studies on the applicability of the impact echo method to the various members of structures are also limited (Chung-YueWang, Chin-LungChiu, Kun-YiTsai Pi-KuanChen, Peng-ChiPeng & Hao-LinWang. (2014)). Columns, beams, slabs, and walls were selected as the various members of concrete structures in this study.

3. IMPACT ECHO METHOD

The impact echo method is based on the use of temporary stress waves created by an elastic impact (M. Sansalone, N. J. Carino, (1986)). For a long time, impacts have been used to create stress pulses because they eliminate a need for a transducer with a large volume while providing higher permeability. The survey method that uses such shock waves was introduced a few years before research was conducted on the ultrasonic velocity method for evaluating the quality of the concrete used for roads. As shock waves are generated by applying an impact, such as with a hammer, on concrete, they are different from ultrasonic waves that are electrically generated and injected into concrete. Shock waves can travel much farther with large magnitudes of energy and can be used for the exploration of thick concrete, such as mass concrete. The impact echo method is used to deduce the strength of the concrete and the measurement of the crack depth as well as thickness, which are related to the quality of concrete, as with ultrasonic pulse velocity method. It is used for the exploration of cavities and buried objects, as well as for the measurement of the pile embedment depth, which cannot be explored or measured with usual ultrasound methods. When a mechanical impact is applied on a surface, bulk waves (P and S waves) that propagate into the specimen with spherical wave fronts and surface waves that propagate along the surface of the specimen with cylindrical wave fronts (R wave) are generated. In this case, the bulk waves are reflected and returned to the surface where stress waves were generated when they meet a discontinuity, such as cracks and cavities, or the interface between different medium layers. As the surface displacement caused by P waves, which were reflected from discontinuities in the medium, such as cracks and cavities, or from the interface between different medium layers, is much larger than that caused by S waves, the waveform detected on the surface can be considered as the waveform caused by the reflected P waves. It is possible to identify flaws in the medium or the position of the interface using the impact echo method, and it is also possible to estimate the defects of concrete when the dimensions of the specimen are known. In addition, when the propagation velocity of P waves is known, it is possible to identify the position of the continuous surface inside the specimen by measuring the arrival time of the reflected wave.

The signal data of the impact echo method undergo time-domain analysis and frequency-domain analysis. However, when the travel distance of the wave is short, it is difficult to determine the accurate arrival time of the compressional and reflected wave because various waves caused by the unique vibration of the object generate complicated shapes. Therefore, for the amplitude spectrum of the short displacement response time, the time-domain data are converted into frequency-domain data through a fast Fourier transform (FFT), and then the data are analyzed to determine the peak frequency.

In the impact echo method, unlike in the resonance method, in which the peak frequency is found while the drive frequency is varied, when broadband elastic waves are generated inside the specimen by applying an impact with a short time width, only the elastic wave of the frequency that meets the resonance condition of the specimen is left. The peak frequency can be found by performing a frequency analysis of this vibration signal, and the size of the specimen can be determined from this peak frequency if the velocity is known. If the concrete surface is excited, the elastic wave generated from the surface propagates into the concrete and returns to the surface. The return time in a concrete structure with a thickness of D can be expressed as Eq. (1).

$$\delta_t = \frac{2D}{C_P} \qquad (1)$$

where δ_t: Elastic wave response time (s)
D: Thickness (mm)
C_p: Velocity of the longitudinal wave (P) inside concrete (m/s)

In case both sides are free ends, if the return time (δ_t) is an integral multiple of the vibration period of the elastic wave applied to the surface, T, constructive interference occurs, thereby increasing the amplitude. Otherwise, the amplitude decreases. The condition of resonance occurrence is shown in Eq. (2).

$$\delta_t = nT = \frac{n}{f} \qquad (n = 1, 2, 3 \cdots) \tag{2}$$

where T: Vibration period of the elastic wave (s)
n: Integer
f: Frequency (Hz)

The frequency that arrives in multiple reflections owing to the initial stress pulse, i.e., the thickness frequency, is expressed as the maximum value in the amplitude spectrum. The approximate expression relating the frequency and thickness is given in Eq. (3).

$$D = c\frac{\delta_t}{2} = \frac{C_P}{2f} \tag{3}$$

where D: Distance to the reflective interface (mm)
C_p: Velocity of P wave (m/s)
f: Thickness frequency (Hz)

In this case, the depth resolution (Δf) differs depending on the depth, and the measurement error is shown in Eq. (4).

$$\delta_D = \frac{c}{2f^2}\Delta f = \frac{2}{c}D^2 = \Delta f \tag{4}$$

Where, δ_D: Measurement error
Δf: Depth resolution

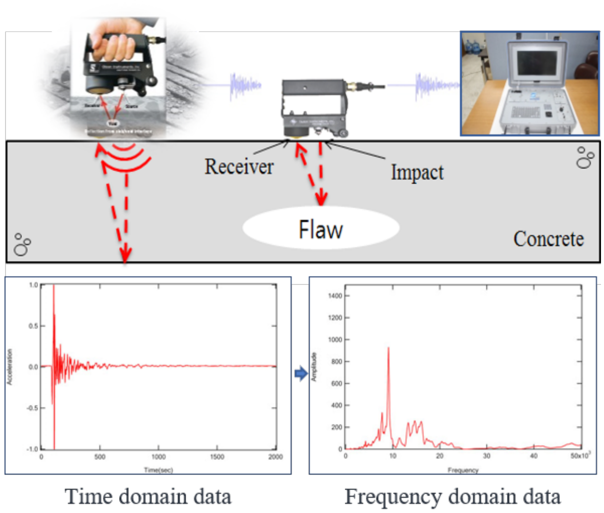

Figure 1. Concept of impact echo method

The impact echo method is performed to evaluate the condition of slabs, columns, walls, pavements, runways, tunnels, and dams. Cavities, honeycombs, cracks, thin layer separation, and other concrete damage, as well as wood, stone, and brick materials, can be found using the impact echo method. Figure 1 shows the conceptual diagram of the impact echo method.

The thinner the structure, the greater the frequency, so the sampling interval should be shorter. The number of data is multiplied by the sampling interval to represent the recording length, which is the total time to record the waveform. If the recording length is too long, there is a fear of obtaining data including waves reflected from the side boundary of the structure. However, if the recording length is too short, the measurement accuracy is lowered. Therefore, it is important to select an appropriate number of data and sampling interval when performing non-destructive experiments using the impact echo method.

4. EXPERIMENT

The specimens for the measurement of concrete member size and thickness were fabricated using the designed strengths of 24, 30, and 40 MPa, as well as the mix ratios in Table 2, as shown in Figure 2. The design of a single-story frame with dimensions 2,400 (width) × 2,400 (depth) × 1,600 (height) mm is shown in Figure 2, and it was fabricated using a minimum number of rebars, as shown in Figure 3.

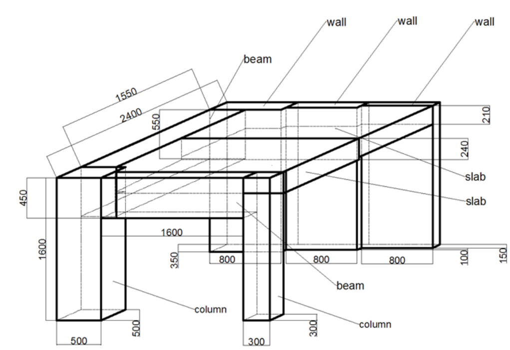

Figure 2. Shape of specimen (mm)

Table 2. Mix Ratio of Concrete

Designed Strength 24 MPa: Mix ratio (kg/m³)					
Cement	Water	Natural sand	Crushed sand	Coarse aggregate	High performance AE reducing agent
314	166	619	267	931	2.51
W/B	52.9%		S/a	49%	
Designed Strength 30 MPa: Mix ratio (kg/m³)					
Cement	Water	Natural sand	Crushed sand	Coarse aggregate	High performance AE reducing agent
383	170	557	240	948	3.06
W/B	44.4%		S/a	45.9%	
Designed Strength 40 MPa: Mix ratio (kg/m³)					
Cement	Water	Natural sand	Crushed sand	Coarse aggregate	High performance AE reducing agent
465	160	532	230	944	3.72
W/B	34.4%		S/a	44.9%	

Figure 3. Form of specimen and concrete curing

Figure 4. Experiment of impact echo method

The column sizes were 250 mm × 250 mm, 300 mm × 300 mm, 400 mm × 400 mm, and 500 mm × 500 mm by concrete compressive strength. The slab thicknesses were 150, 180, 210, and 240 mm by concrete compressive strength, and the beam sizes were 250, 350, 450, and 550 mm by concrete compressive strength. Table 3 shows the list of the specimens. To determine whether the impact echo method could be used for quality control, the size of each concrete member was measured using the impact echo method and the method's size estimation accuracy was found, the size of each concrete member was measured using the impact echo method. The experiment was repeatedly performed at the planned point for each member in accordance with ASTM C 1384-04 after 28 days by removing the mold and drawing grids as shown in Figure 4. The experimental sequence was as follows.

1) Apply an impact
2) Record the detected wave signal
3) Convert the time-domain signal into the frequency-domain signal using FFT
4) Calculate the peak frequency from the frequency-domain signal
5) Calculate the velocity of the compressional wave

The experiment results for the column, slab, and beam members are shown in Table 4, Table 5, and Table 6, respectively. As shown in Table 4, the results of the concrete column size estimation experiment using the impact echo method for the column members with a designed strength of 24 MPa revealed that the measured size was 248.5 mm, while the estimated size by the non-destructive testing

method was 239.9 mm for the column with a specified size of 250 mm. For the column with a specified size of 300 mm, the measured size was 298.0 mm, and the estimated size was 301.3 mm. For the column with a specified size of 400 mm, the measured size was 392.5 mm, and the estimated size was 404.6 mm. For the column with a specified size of 500 mm, the measured size was 496.5 mm, and the estimated size was 499.3 mm.

The error rate was 3.5% for the column with a specified size of 250 mm, 1.1% for the column with a specified size of 300 mm, 3.1% for the column with a specified size of 400 mm, and 0.6% for the column with a specified size of 500 mm. The average error rate was 2.1%.

Table 3. List of Concrete Member

Member	Specimen Name		Detail
Column	RC24S250	RC30S400	RC: Reinforced Concrete Designed Strength: 24, 30, 40 MPa S: Size of column 250, 300, 400, 500 mm
	RC24S300	RC30S500	
	RC24S400	RC40S250	
	RC24S500	RC40S300	
	RC30S250	RC40S400	
	RC30S300	RC40S500	
Slab	RC24T150	RC30T210	RC: Reinforced Concrete Designed Strength: 24, 30, 40 MPa T: Thickness of slab 150, 180, 210, 240 mm
	RC24T180	RC30T240	
	RC24T210	RC40T150	
	RC24T240	RC40T180	
	RC30T150	RC40T210	
	RC30T180	RC40T240	
Beam	RC24D250	RC30D450	RC: Reinforced Concrete Designed Strength: 24, 30, 40 MPa D: Depth of beam 250, 350, 450, 550 mm
	RC24D350	RC30D550	
	RC24D450	RC40D250	
	RC24D550	RC40D350	
	RC30D250	RC40D450	
	RC30D350	RC40D550	

The results of the experiment using the impact echo method for the column members with the designed strength of 30 MPa revealed that, for the column with a specified size of 250 mm, the measured size was 249.5 mm, while the estimated size was 253.2 mm. For the column with a specified size of 300 mm, the measured size was 298.0 mm, and the estimated size was 303.4 mm. For the column with a specified size of 400 mm, the measured size was 399.0 mm, and the estimated size was 412.0 mm. For the column with a specified size of 500 mm, the measured size was 493.0 mm, and the estimated size was 527.7 mm. The error rate was 1.5% for the column with a specified size of 250 mm, 1.8% for the column with a specified size of 300 mm, 3.3% for the column with a specified size of 400 mm, and 7.0% for the column with a specified size of 500 mm. The average error rate was found to be 3.4%.

Table 4. Analysis of the Experiment Results (Column)

Name	Results [mm]							
RC24S250	Measured size	249 × 248						
	Estimated size	247	222	236	229	247	Ave.	Error
		244	247	247	236	244	239.9	3.5%
RC24S300	Measured size	299 × 297						
	Estimated size	312	300	300	300	289	Ave.	Error
		312	300	300	300	300	301.3	1.1%
RC24S400	Measured size	390 × 395						
	Estimated size	421	400	381	421	400	Ave.	Error
		421	421	400	381	400	404.6	3.1%
RC24S500	Measured size	495 × 498						
	Estimated size	514	489	467	514	489	Ave.	Error
		514	489	514	489	514	499.3	0.6%
RC30S250	Measured size	249 × 250						
	Estimated size	258	250	250	258	250	Ave.	Error
		250	250	258	250	258	253.2	1.5%
RC30S300	Measured size	300 × 296						
	Estimated size	290	311	300	300	300	Ave.	Error
		300	311	311	300	311	303.4	1.8%
RC30S400	Measured size	398 × 400						
	Estimated size	421	400	395	444	400	Ave.	Error
		421	444	400	395	400	412	3.3%
RC30S500	Measured size	488 × 498						
	Estimated size	500	531	567	571	604	Ave.	Error
		500	500	537	500	467	527.7	7.0%
RC40S250	Measured size	247 × 251						
	Estimated size	257	257	257	250	250	Ave.	Error
		273	257	250	257	257	256.5	3.0%
RC40S300	Measured size	301 × 297						
	Estimated size	300	300	300	300	311	Ave.	Error
		311	300	300	311	300	303.3	1.4%
RC40S400	Measured size	400 × 398						
	Estimated size	400	400	400	400	420	Ave.	Error
		400	467	443	420	400	415	4.0%
RC40S500	Measured size	485 × 499						
	Estimated size	567	500	500	500	500	Ave.	Error
		500	500	531	531	500	512.9	4.2%

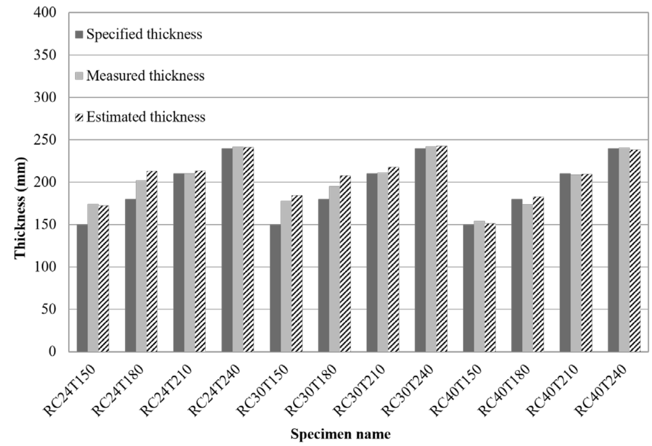

Figure 5. Comparison of the experiment results (slab)

The results of the experiment using the impact echo method for the column members with the designed strength of 40 MPa revealed that, for the column with a specified size of 250 mm, the measured size was 249.0 mm, and the estimated size was 256.5 mm. For the column with a specified size of 300 mm, the measured size was 299.0 mm, and the estimated size was 303.3 mm. For the column with a specified size of 400 mm, the measured size was 399.0 mm, and the estimated size was 415.0 mm. For the column with a specified size of 500 mm, the measured size was 492.0 mm, and the estimated size was 512.9 mm. The error rate was 3.0% for the column with a specified size of 250 mm, 1.4% for the column with a specified size of 300 mm, 4.0% for the column with a specified size of 400 mm and 4.2% for the column with a specified size of 500 mm. The average error rate was 3.2%. The overall error rate by column member size was 2.9%, confirming that, by estimating the sizes of members using a non-destructive testing method, quality management is possible.

As shown in Table 5 and Figure 5, the results of the experiment using the impact echo method to estimate the thickness values of slab members with a designed strength of 24 MPa revealed that, for the slab with a specified thickness of 150 mm, the measured thickness was 174.3 mm, while the estimated thickness using the non-destructive testing method was 172.7 mm, resulting in an estimation error rate of 0.9%. For the slab with a specified thickness of 180 mm, the measured thickness was 202.3 mm, and the estimated thickness was 212.9 mm, resulting in an estimation error rate of 5.0%. For the slab with a specified thickness of 210 mm, the measured thickness was 210.0 mm, and the estimated thickness was 213.3 mm, resulting in an estimation error rate of 1.5%. For the slab with a specified thickness of 240 mm, the measured thickness was 241.7 mm, and the estimated thickness was 241.1 mm, resulting in an estimation error rate of 0.2%. The overall average error rate was 1.9%, indicating that the derived results were highly reliable. For the slab with a specified thickness of 150 mm, the difference between the specified thickness and measured thickness was 24.3 mm, and the difference between the measured thickness and estimated thicknesses was 1.6 mm. For the slab with a specified thickness of 180 mm, the difference between the specified thickness and measured thickness was 22.3 mm, and the difference between the measured thickness and estimated thicknesses was 10.6 mm. For the slab with a specified thickness of 210 mm, the difference between the specified thickness and measured thickness was 0.0 mm, and the difference between the measured thickness and estimated thicknesses was 3.3 mm. For the slab with a specified thickness of 240 mm, the difference between the specified thickness and measured thickness was 1.7 mm, and the difference between the measured thickness and estimated thicknesses was 0.6 mm.

As shown in Table 5, the results of the concrete slab thickness estimation experiment using the impact echo method for the slab members with the designed strength of 30 MPa revealed that, for the slab with a specified thickness of 150 mm, the measured thickness was 178.3 mm, while the estimated thickness using the non-destructive testing method was 184.1 mm, resulting in an estimation error rate of 3.2%. For the slab with a specified thickness of 180 mm, the measured thickness was 195.0 mm, and the estimated thickness was 207.8 mm, resulting in an estimation error rate of 6.2%. For the slab with a specified thickness of 210 mm, the measured thickness was 211.0 mm, and the estimated thickness was 218.2 mm, resulting in an estimation error rate of 3.3%. For the slab with a specified thickness of 240 mm, the measured thickness was 242.3 mm, and the estimated thickness was 242.8 mm, resulting in an estimation error rate of 0.2%. The overall average error rate was 3.2%, indicating that highly reliable results were derived. For the slab member with a specified thickness of 150 mm, the difference between the specified thickness and measured thickness was 28.3 mm, and the difference between the measured thickness and estimated thicknesses was 5.8 mm. For the slab member with a specified thickness of 180 mm, the difference between the specified thickness and measured thickness was 15.0 mm, and the difference between the measured thickness and estimated thicknesses was 12.8 mm. For the slab member with a specified thickness of 210 mm, the difference between the specified thickness and measured thickness was 1.0 mm, and the difference between the measured thickness and estimated thicknesses was 7.2 mm. For the slab member with a specified thickness of 240 mm, the difference between the specified thickness and measured thickness was 2.3 mm, and the difference between the measured thickness and estimated thicknesses was 0.5 mm.

The results of the concrete slab thickness estimation experiment using the impact echo method for the slab members with the designed strength of 40 MPa revealed that, for the slab with a specified thickness of 150 mm, the measured thickness was 154.3 mm, while the estimated thickness using the non-destructive testing method was 151.2 mm, as shown in Table 5, resulting in an estimation error rate of 2.1%. For the slab with a specified thickness of 180 mm, the measured thickness was 173.7 mm, and the estimated thickness was 182.8 mm, resulting in an estimation error rate of 5.0%. For the slab with a specified thickness of 210 mm, the measured thickness was 208.7 mm, and the estimated thickness was 209.8 mm, resulting in an estimation error rate of 0.5%. For the slab with a specified thickness of 240 mm, the measured thickness was 240.7 mm, and the estimated thickness was 238.3 mm, resulting in an estimation error rate of 1.0%. The overall average error rate was 2.2%, indicating that highly reliable results were derived.

Table 5. Analysis of the Experiment Results (Slab)

No	Specimen Name	Specified thickness	Measured thickness		S-M	Estimated thickness			Average of estimated thickness	Error ratio	Average of Error ratio	
1	RC24T150	150	171	174.3	-24.3	171	171	165	172.7	0.9	1.9	2.4
			175			171	174	174				
			177			174	177	177				
2	RC24T180	180	205	202.3	-22.3	213	209	209	212.9	5.0		
			204			213	213	218				
			198			212	217	212				
3	RC24T210	210	211	210.0	0.0	210	214	214	213.3	1.5		
			210			210	214	219				
			209			210	219	210				
4	RC24T240	240	241	241.7	-1.7	239	245	245	241.1	0.2		
			242			245	239	239				
			242			245	239	234				
5	RC30T150	150	180	178.3	-28.3	180	183	183	184.1	3.2	3.2	
			180			183	183	186				
			175			186	186	187				
6	RC30T180	180	199	195.0	-15.0	206	203	199	207.8	6.2		
			196			203	219	210				
			190			206	210	214				
7	RC30T210	210	209	211.0	-1.0	219	214	214	218.2	3.3		
			212			219	223	223				
			212			219	219	214				
8	RC30T240	240	242	242.3	-2.3	245	243	245	242.8	0.2		
			242			245	245	233				
			243			245	239	245				
9	RC40T150	150	154	154.3	-4.3	157	157	154	151.2	2.1	2.2	
			153			151	151	149				
			156			146	142	154				
10	RC40T180	180	177	173.7	6.3	187	177	177	182.8	5.0		
			172			190	170	187				
			172			190	187	180				
11	RC40T210	210	209	208.7	1.3	210	214	210	209.8	0.5		
			206			214	210	205				
			211			205	210	210				
12	RC40T240	240	242	240.7	-0.7	234	237	237	238.3	1.0		
			240			248	242	231				
			240			231	248	237				

For the slab member with a specified thickness of 150 mm, the difference between the specified thickness and measured thickness was 4.3 mm, and the difference between the measured thickness and estimated thickness was 3.1 mm. For the slab member with specified thickness of 180 mm, the difference between the specified thickness and measured thickness was 6.3 mm, and the difference between the measured thickness and estimated thickness was 9.1 mm. For the slab member with a specified thickness of 210 mm, the difference between the specified thickness and measured thickness was 1.3 mm, and the difference between the measured thickness and estimated thickness was 1.1 mm. For the slab member with a specified thickness of 240 mm, the difference between the specified thickness and measured thickness was 0.7 mm, and the difference between the measured thickness and estimated thickness was 2.4 mm.

As shown in Figure 6, the results of estimating the concrete slab thickness using the impact echo method for the slab members with designed strengths of 24, 30, and 40 MPa revealed that the overall average error rate was 2.4%, indicating that highly reliable results were derived. This confirms that the quality control of concrete slabs is possible for existing structures as well as structures under construction.

As shown in Table 6, the results of the concrete beam member depth estimation experiment using the impactecho

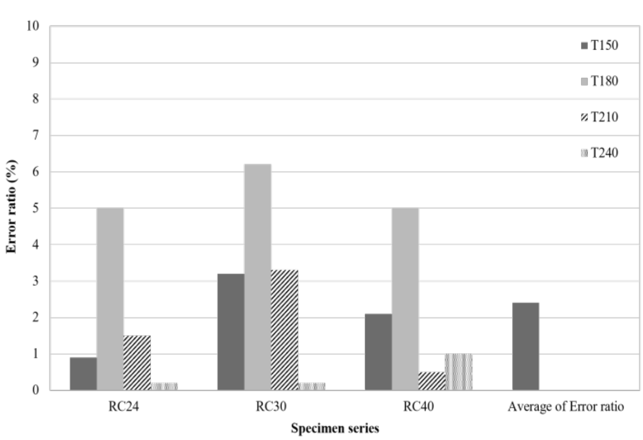

Figure 6. Comparison of the error ratio (slab)

method for the beam members with a designed strength of 24 MPa revealed that, for the beam member with a specified depth of 250 mm, the measured depth was 256.3 mm, while the estimated depth using the non-destructive testing method was 281.3 mm, resulting in an estimation error rate of 9.8%. For the beam member with a specified depth of 350 mm, the measured depth was 364.3 mm, and the estimated depth using the non-destructive testing method was 413.2 mm, resulting in an estimation error rate of 13.4%. For the beam member with a specified depth of 450 mm, the measured depth was 434.3 mm, and the estimated depth using the non-destructive testing method was 498.2 mm, resulting in an estimation error rate of 14.7%. For the beam member with a specified depth of 550 mm, the measured depth was 542.0 mm, and the estimated depth using the non-destructive testing method was 601.8 mm, resulting in an estimation error rate of 14.4%. As a result of estimating the depth of the beam members using the impact echo method, an overall average error rate of 13.1% was derived. For the beam member with a specified depth of 250 mm, the difference between the specified depth and measured depth was 6.3 mm, and the difference between the measured depth and estimated depth was 25.0 mm. For the beam member with a specified depth of 350 mm, the difference between the specified depth and measured depth was 14.3 mm, and the difference between the measured depth and estimated depth was 48.9 mm. For the beam member with a specified depth of 450 mm, the difference between the specified depth and measured depth was 15.7 mm, and the difference between the measured depth and estimated depth was 63.9 mm. For the beam member with a specified depth of 550 mm, the difference between the specified depth and measured depth was 8.0 mm, and the difference between the measured depth and estimated depth was 59.8 mm.

Table 6. Analysis of the Experiment Results (Beam)

No	Specimen Name	Specified depth	Measured depth		S-M	Estimated depth			Average of estimated depth	Error ratio	Average of Error ratio	
1	RC24D250	250	261	256.3	-6.3	270	294	282	281.3	9.8	13.1	9.7
			255			282	282	282				
			253			285	285	270				
2	RC24D350	350	354	364.3	-14.3	395	395	395	413.2	13.4		
			359			411	428	428				
			380			411	428	428				
3	RC24D450	450	430	434.3	15.7	467	467	489	498.2	14.7		
			430			514	514	514				
			443			489	514	489				
4	RC24D550	550	550	542.0	8.0	628	628	594	601.8	14.4		
			543			573	616	594				
			533			605	605	573				
5	RC30D250	250	246	241.7	8.3	263	257	263	262.9	8.8	8.7	
			242			251	272	270				
			237			263	270	257				
6	RC30D350	350	347	365.0	-15.0	381	381	367	399.1	9.3		
			365			395	395	412				
			383			428	411	422				
7	RC30D450	450	430	430.0	20.0	447	447	447	458.3	6.6		
			430			467	447	489				
			430			467	467	447				
8	RC30D550	550	560	554.3	-4.3	616	616	616	609.9	10.0		
			556			605	616	616				
			547			616	594	594				
9	RC40D250	250	236	236.3	13.7	251	251	257	252.3	6.8	7.2	
			237			245	257	251				
			236			251	257	251				
10	RC40D350	350	343	367.7	-17.7	367	367	381	394.6	7.3		
			370			381	411	411				
			390			411	411	411				
11	RC40D450	450	420	424.3	25.7	447	467	447	460.8	8.6		
			423			447	447	467				
			430			489	489	447				
12	RC40D550	550	544	541.0	9.0	594	563	573	573.4	6.0		
			539			583	583	583				
			540			574	554	554				

The results of the concrete beam member depth estimation experiment using the impact echo method for the beam members with a designed strength of 30 MPa revealed that, for the beam member with a specified depth of 250 mm, the measured depth was 241.7 mm, while the estimated depth using the non-destructive testing method was 262.9 mm, as shown in Table 6, resulting in an estimation error rate of 8.8%. For the beam member with a specified depth of 350 mm, the measured depth was 365.0 mm, and the estimated depth using the non-destructive testing method was 399.1 mm, resulting in an estimation error rate of 9.3%. For the beam member with a specified depth of 450 mm, the measured depth was 430.0 mm, and the estimated depth using the non-destructive testing method was 458.3 mm, resulting in an estimation error rate of 6.6%. For the beam member with a specified depth of 550 mm, the measured depth was 554.3 mm, and the estimated depth using the non-destructive testing method was 609.9 mm, resulting in an estimation error rate of 10.0%. The overall average error rate was 8.7%, indicating high reliability

For the beam member with a specified depth of 250 mm, the difference between the specified depth and measured depth was 8.3 mm, and the difference between the measured depth and estimated depth was 21.2 mm. For the beam member with a specified depth of 350 mm, the difference between the specified depth and measured depth was 15.0 mm, and the difference between the measured depth and estimated depth was 34.1 mm. For the beam member with a specified depth of 450 mm, the difference between the specified depth and measured depth was 20.0 mm, and the difference between the measured depth and estimated depth was 28.3 mm. For the beam member with a specified depth of 550 mm, the difference between the specified depth and measured depth was 4.3 mm, and the difference between the measured depth and estimated depth was 55.6 mm.

The results of the concrete beam member depth estimation experiment using the impact echo method for the beam members with a designed strength of 40 MPa revealed that, for the beam member with a specified depth of 250 mm, the measured depth was 236.3 mm, while the estimated depth using the non-destructive testing method was 252.3 mm, as shown in Table 6, resulting in an estimation error rate of 6.8%. For the beam member with a specified depth of 350 mm, the measured depth was 367.7 mm, and the estimated depth using the non-destructive testing method was 394.6 mm, resulting in an estimation error rate of 7.3%. For the beam member with a specified depth of 450 mm, the measured depth was 424.3 mm, and the estimated depth using the non-destructive testing method was 460.8 mm, resulting in an estimation error rate of 8.6%. For the beam member with a specified depth of 550 mm, the measured depth was 541.0 mm, and the estimated depth using the non-destructive testing method was 573.4 mm, resulting in an estimation error rate of 6.0%. As a result of estimating the depth of the beam members using the impact echo method, an overall average error rate of 7.2% was derived, indicating that the results were highly reliable. For the beam member with a specified depth of 250 mm, the difference between the specified depth and measured depth was 13.7 mm, and the difference between the measured depth and estimated depth was 16.0 mm. For the beam member with a specified depth of 350 mm, the difference between the specified depth and measured depth was 17.7 mm, and the difference between the measured depth and estimated depth was 26.9 mm. For the beam member with a specified depth of 450 mm, the difference between the specified depth and measured depth was 25.7 mm, and the difference between the measured depth and estimated depth was 36.5 mm. For the beam member with a specified depth of 550 mm, the difference between the specified depth and measured depth was 9.0 mm, and the difference between the measured depth and estimated depth was 32.4 mm.

As shown in Figure 7, the results of estimating the concrete beam member depth using the impact echo method for the beam members with designed strengths of 24, 30, and 40 MPa revealed that the overall average error rate was 9.7%, indicating that highly reliable results were derived. This confirms that quality control of concrete beams is possible for existing structures as well as structures under construction.

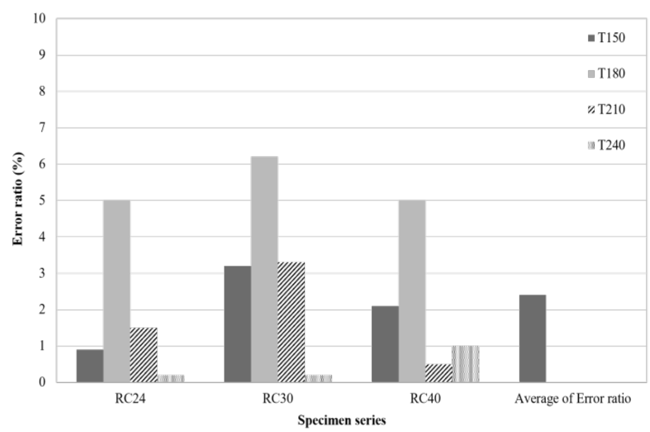

Figure 7. Comparison of the error ratio (beam)

5. CONCLUSIONS

The purpose of this study was to estimate the size, thickness and depth of concrete column, slab, and beam members using the impact echo method, a non-destructive testing method, as the method for identifying the size estimation accuracy according to the member types of concrete structures. To achieve this purpose, six single-story frame specimens composed of column, slab, and beam members in different sizes were fabricated, and a non-destructive testing experiment was conducted to estimate the sizes of the members. As a result of estimating the sizes of the concrete column members using the impact echo method, the error rate of the designed strength of 24 MPa is 2.1%, the error rate of the designed strength of 30 MPa is 3.4% and the error rate of the designed strength of 40 MPa is 3.2% were observed. The overall error rate by column member strength and size was found to be 2.9%. Furthermore, as a result of estimating the depth of the concrete beam members, the error rate of the designed strength of 24 MPa is 13.1%, the error rate of the designed strength of 30 MPa is 8.7% and the error rate of the designed strength of 40 MPa is 7.2% were observed. The overall error rate was 9.7%. As a result of estimating the thickness of the concrete slab members, the error rate of the designed strength of 24 MPa is 1.9%, the error rate of the designed strength of 30 MPa is 3.2% and the error rate of the designed strength of 40 MPa is 2.2% were observed. The overall error rate was 2.4%. These results confirmed that quality control of the members of concrete structures is possible by estimating their sizes using a non-destructive testing method.

In case there is no information on the sizes of the column, slab, and beam members of the existing concrete structures, the estimation of the sizes of various members using the impact echo method can be applied to the re-creation of drawings for buildings and facilities whose structural drawings are lost and the maintenance of structures, among others

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