Concrete Tester & Surveyor

Tomoaki SAKAI Dr. Eng. P.E.
NITTO Construction Inc.
Ohmucho, Hokkaido, JAPAN
Topics of today

• Theory of mechanical impedance measurement
  – What mechanical impedance is.
  – How to measure the mechanical impedance by hammer blow
• Estimation method of compressive strength of concrete
  – Elastic property of the concrete
  – Considering on the Estimation error
• Comparison between CTS and traditional rebound hammer
  – Theory & applicability
Theory of CTS  **Mechanical Impedance Method (MIM)**

In the case of MIM no plunger is involved and the hammer directly blow the concrete surface.

Driving force changes in accordance with the velocity of the hammer and the mechanical impedance of the hammer mass and spring coefficient of the concrete surface.

Both the rebound hammer and MIM are using the same way for generating the driving force by hammer blow. However the mechanisms are different. Indirect drive and direct drive.
Basic theory of MIM (1)

\[ E_H = \frac{1}{2} M V_0^2 \]  
Kinematic energy of hammer

\[ E_C = \frac{1}{2} K D_{\text{max}}^2 \]  
Potential energy of the concrete surface

The hammer with mass of \( M \) and velocity \( V_0 \) blows the concrete surface having spring coefficient \( K \). Displacement of the concrete surface due to the hammer blow is \( D \).

\[ E_H = E_C \Rightarrow M V_0^2 = K D_{\text{max}}^2 \]  
energy equilibrium
Basic theory of MIM (2)

\[ MV_0^2 = KD_{\text{max}}^2 = \frac{F_{\text{max}}^2}{K} \]

\[ D = \frac{F}{K} \]

\[ \sqrt{MK} = \frac{F_{\text{max}}}{V_0} \]

This is the Mechanical Impedance

\[ K = \frac{1}{M} \cdot \frac{F_{\text{max}}^2}{V_0^2} \]

The spring coefficient of the concrete surface can be determined by the maximum Driving force and initial velocity of the hammer.
Motion equation analysis

\[ M \frac{d^2x}{dt^2} + 2\pi rz \frac{dx}{dt} + 2\pi kx^2 = 0 \]

- \( M \): mass of hammer
- \( R \): radius of spherical segment of hammer
- \( z \): Acoustic impedance of concrete
- \( k \): spring coefficient of concrete surface
- \( x \): displacement of concrete surface
- \( 2\pi Rx \): contact area

\[ x_{i+1} = \frac{1}{1 + \frac{\pi Rz \delta t}{M} x_i} \left( 2x_i + \frac{\pi Rz \delta t}{M} x_ix_{i-1} - \frac{2\pi k \delta t^2}{M} x_i^2 - x_{i-1} \right) \]

numerical solution by means of finite difference method
Results of motion equation analysis

Calculated force wave form

Actual driving force wave form
Spring coefficient formula

\[ k' = \frac{M^N A_{\text{max}}^3}{V^4} \]
Measurement of mechanical impedance

\[ F_{\text{max}} = MA_{\text{max}} \]

[Force]=[Mass] \times [Acceleration]

\[ V_0 = \int_0^T Adt \]

Time integration of acceleration makes speed

If acceleration of hammer is measured, Force and velocity of hammer are given.

Mechanical impedance is given
Strength Estimation Method

\[ \sigma_U = E \varepsilon_U \]

\( E \): Elastic modulus

\( \varepsilon_U \): 2000 to 2500 micro-strain
Reduction rate of secant elastic modulus

Reduction rate depends on compressive strength of concrete.

No reduction rate is observed for higher compressive strength concrete.
Relationship between measured spring coefficient and compressive strength

For High strength concrete

For Normal strength concrete

$y = 0.9997x$

$R = 0.882$

$Z^4$

$Z^3$
CTS technology

Structure of CTS-02

- Accelerometer
- Hammer head
Substantial Waveform (Symmetric)

The graph shows a symmetric waveform with a peak at 300 μs. The x-axis represents time in seconds, ranging from 0 to 0.0004 seconds, and the y-axis represents force in acceleration, ranging from 0 to 7000. The waveform is symmetric for a peak, indicating that it rises and falls equally on both sides of the peak point.
Schematic Diagram of Impact Waveform
(First Half, Active Side)

This area means initial speed of hammer. Hammer pushing onto concrete surface.
Schematic Diagram of Impact Waveform (Second Half, Reactive Side)

If perfect elastic body, Coefficient of restitution is 1. Therefore first half and latter half area are equal.

This area is rebound speed of hammer. Hammer being pushed out by the concrete.
Examination of Mechanical Impedance

Hit directly

Hit with paper covering
Influence of surface plasticity

\[ Z_a = 4699 \text{(No paper)} \]
\[ Z_a = 3355 \text{(With paper)} \]
\[ Z_R = 4627 \text{(With paper)} \]
\[ Z_R = 4685 \text{(No paper)} \]

\[ \text{With Paper} \quad = 72\% \]
\[ \frac{\text{With Paper}}{\text{No Paper}} \]
\[ \text{No Paper} \quad = 99\% \]
Wave form of impact force for integrity concrete
Surface deteriorated concrete

![Graph showing the relationship between force and time for surface deteriorated concrete.](image-url)
Severely deteriorated concrete
Concrete with inside deterioration

This wave form is often observed for water way concrete.
Three values of CTS output

• STR : Compressive Strength of Concrete [N/mm²]
  • This calculates by reactive mechanical impedance

• Index: inverse value of coefficient of restitution
  • This calculates by the ratio between Za and Zr. This value shows the deterioration of concrete surface

• Status: number of local peaks
  • Numbers of local peaks before and after maximum peak are shown. This values indicate the delamination of concrete surface.
Traditional instrument for concrete strength estimation:

Rebound Hammer

Dr. Schmidt developed in 1940’s
# CTS vs. Rebound Hammer

<table>
<thead>
<tr>
<th></th>
<th>CTS</th>
<th>Rebound Hammer</th>
</tr>
</thead>
<tbody>
<tr>
<td>works</td>
<td>Hammer blow</td>
<td>Hammer blow blow</td>
</tr>
<tr>
<td>Basic theory</td>
<td>Resistance</td>
<td>Restitution degree</td>
</tr>
<tr>
<td>requirements</td>
<td>Elastic deformation</td>
<td>Plastic deformation</td>
</tr>
<tr>
<td>measures</td>
<td>MI, restitution rate</td>
<td>Restitution degree</td>
</tr>
<tr>
<td>technology</td>
<td>Digital measurement</td>
<td>Mechanical instrument</td>
</tr>
</tbody>
</table>
CTS vs. Rebound Hammer
technological back ground (computer)

ENIAC 1946
Rebound hammer era

PIV 2005
CTS era
Structure of Rebound hammer

JIS A 1153 2003

Structure and measuring method of Rebound hammer are defined in JIS

- Spring 700~840N/m
- Hammer mass 360g~380g
- Plunger tip radius 24.0~25.5mm
- Driving energy 2.10~2.30N·m
Mechanism of Schmidt hammer

The Kinematic model of the Schmidt hammer is an analogy of the pile driving.

Plunger tip: Spring supported end

Consideration from the stress wave theory is necessary to understand what is measured by rebound value of Schmidt hammer.

Soil Foundation modeled by spring, slider and damper
Result of numerical calculation of wave forms at plunger head

If backward wave is compressive force, hammer will rebound.
Figure shows the results of the numerical calculations as the relationship between the spring constant of the concrete surface and the rebound values. The relationship between them is non-linear and if the spring constant of the concrete surface becomes higher, the trend of the rebound value is saturated. And also, we can say that the rebound value is depended on the elastic characteristics of the concrete.
Rebound Hammer vs. CTS

<table>
<thead>
<tr>
<th></th>
<th>MC Nylon</th>
<th>Hard stone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wave speed</td>
<td>1900m/s</td>
<td>5600m/s</td>
</tr>
<tr>
<td>Rebound Hammer</td>
<td>55</td>
<td>55</td>
</tr>
<tr>
<td>CTS STR</td>
<td>8.3</td>
<td>25.0</td>
</tr>
<tr>
<td>Index</td>
<td>1.0</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Materials are almost perfectly elastic. The rebound values are same, however Young's modulus are different. CTS's strength (mechanical impedance) values are in proportion to wave speed.
Strength by Rebound Hammer

Rebound value vs. compressive strength

\[ y = 1.9405x - 17.501 \]

\[ R = 0.533 \]

No good relationship
Meaningful correlation is observed

Impedance vs. compressive strength

\[ y = 0.3275e^{0.3345x} \]

\[ R = 0.855 \]
Advantage of CTS-02

1. Estimation of Compressive Strength of Concrete (Normal Concrete, High Compressive Concrete)

2. Detection of Deterioration (Plasticity) of Concrete Surface

3. Detection of Delamination, void and honeycomb near Concrete Surface

4. Detection of weakness of Aggregate on Concrete Surface

5. Higher degree of accuracy
Advantage of CTS-02

6. Automatic correction for measured data outside the mean value (+/- 20%)

7. No need to polish the testing surface

8. No indentation/damage left on concrete surface

9. Data and results are saved internally - no mistakes or misreading of data
Hot news on CTS applications

Ceiling plates falling accident was happened in Sasago tunnel on last November.
This accident became a trigger to starting NDT of the anchor Volts.

Two test methods were applied for BDT of the chemical anchor.
(1) Da-on (打音), sounding method.
(2) CTS as the similar as sounding
What should be checked

Measuring the spring coefficient of adhesive,
Integrity of Volt will be estimating.

Volt = mass

Adhesive = spring + damper

Characteristics of adhesive
Hardness  rigidity (Elasticity)
Cohesiveness  wave transfer
Mechanical impedance

This is the index value of stiffness

\[ v = \frac{F}{Z} \quad Z = \frac{F}{v} \]

- \( F \): force
- \( v \): speed
- \( Z \): mechanical impedance

If mechanical impedance is large, move hard when external force is applied.
Actual Test in tunnel
Simulated anchor volt for examination
Measured wave form(1)

Filling rate 100%, integrity vlots
Measured wave form (2)

Non symmetric for a peak

Filling rate 25%, no good volt
Measured wave form (3)

Double wave are observed

Filling rate 0% volt,
Evaluation by wave form

Filling rate 100%
Filling rate 60%
Filling rate 25%
Integrity evaluation of chemical anchor volt by MIM

<table>
<thead>
<tr>
<th>integrity</th>
<th>Non integrity</th>
<th>property</th>
</tr>
</thead>
<tbody>
<tr>
<td>impedance</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>symmetry</td>
<td>symmetric</td>
<td>Non symmetric</td>
</tr>
</tbody>
</table>
Evaluation

Evaluation

Machanical impedance

Filling rate 25% data are scattered

Non linearity
Non integrity volt
2009 The Monozukuri (Craftsmanship) Nippon Grand Award 【Special Award】
2010 Local Commendation for Invention of Hokkaido
【Prize of Director-General, Small and Medium sized Enterprises】
Technology Registration on CTS

(1) New Technology Information System (NETIS) of Ministry of Land, Infrastructure, Transport and Tourism (MLIT) in Japan
   Registration Date: September 6th, 2006
   Registration Number: HK-060013

(2) New Technology Information System of Hokkaido
   Registration Date: September 20th, 2006
   Registration Number: 20060015

(3) Agricultural and Rural Development Information Center (ARIC)
   Registration Date: November 21st, 2006
   Registration Number: 261
Academic Report Released

(Total 50 Over Reports)

● Japan Society of Civil Engineers (JSCE) 20 Reports
● The Japanese Society for Non-Destructive Inspection (JSNDI) 18 Reports
● The Japanese Society of Irrigation, Drainage and Rural Engineering (JSIDRE) 6 Reports
● Japan Concrete Institute (JCI) 3 Reports
● Japan Association of Agricultural Engineering Enterprises (JAGREE) 2 Reports
● International Conference on Advanced Technology in Experimental Mechanics 2011 (ATEM’11) 1 Report
● Structural Fault and Repair 2012, 2 Reports
Number of Units Sold by country  (as of Feb. 05, 2013)

<table>
<thead>
<tr>
<th>Country</th>
<th>Units Sold</th>
</tr>
</thead>
<tbody>
<tr>
<td>Japan</td>
<td>329</td>
</tr>
<tr>
<td>South Korea</td>
<td>12</td>
</tr>
<tr>
<td>USA</td>
<td>4</td>
</tr>
<tr>
<td>China</td>
<td>13</td>
</tr>
<tr>
<td>Other countries</td>
<td>2</td>
</tr>
</tbody>
</table>

Total: 360