RESEARCH ON THE LONG-TERM BEHAVIOUR AND EVALUATION OF LINING CONCRETE OF THE SEIKAN TUNNEL

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ABSTRACT

Some of the important issues involved in undersea tunnels distinct from land tunnels include examining what measures should be taken against inexhaustible water and huge hydraulic pressure during construction and how to maintain the structural soundness after completion. An undersea tunnel that loses its soundness and causes flooding or any other forms of accidents while still in service is likely to put human lives at risk and pose a threat to the safety of the social infrastructure, and the restoration of such structure may become impossible in some cases. However, because much of the behaviour of tunnels under operation is still yet to be defined, the maintenance of existing undersea tunnels is practically limited to the treatment of symptoms based on past experiences, as in the case for land tunnels. Focusing on the long-term measurements of Seikan Tunnel that have been recorded since 1988, this paper organizes and analyzes their results, examines the mechanism of long-term behaviour of tunnel lining, and proposes a new soundness evaluation methodology for the undersea tunnel lining (Tuchiya, 2007).

Key words: cut-off grouting, evaluation of lining concrete, long-term measurement, undersea tunnel, water head (IGC: H5)

INTRODUCTION

Ever since the first construction of Kammon Tunnel for conventional railways in 1944, the research and development of undersea tunnel excavation technologies have been undertaken in Japan through construction of the Shinkansen Bullet Train Kammon Tunnel, Daiba Tunnel on the JR Keiyo Line, Seikan Tunnel and the Tokyo Aqua Line Tunnel.

Unlike land tunnels, the most important issues for undersea tunnels are to examine what measures should be taken against inexhaustible water and huge hydraulic pressure during construction and how to maintain the structural soundness after completion. An undersea tunnel that loses its soundness and causes flooding or any other forms of accidents while still in service is likely to put human lives at risk and pose a threat to the great threat to the safety of the social infrastructure, and the restoration of such structure may become impossible in some cases.

Tunnels are generally structurally stable, enclosed by rock mass and supported by the ground arching effect sustained after the completion of construction. In some cases under special geographical and geological conditions, however, tunnel deformations are observed where their linings are subjected to loads.

As these deformations appear with the passage of time, the monitoring activities usually start in the form of cross-sectional measurements after abnormalities are confirmed. There have been some reports on such measurements (Nozawa et al., 1992; Katayose et al., 1997), and studies on the long-term deformation prediction have recently been carried out (Matsunaga et al., 2005; Japanese Society of Civil Engineering, 2003).

While several large-scale investigations have been carried out on linings and other factors during a specific period of time (Emura and Miyatake, 1992; Kusuhara, 1980), there have been few researches on the long-term behaviour of undersea tunnels, partly due to the fact that it has not been very long since they were constructed.

Since much of the behaviour of tunnels under operation is still yet to be defined, the maintenance of existing undersea tunnels is practically limited to the treatment of symptoms based on past experiences.

The Seikan Tunnel is a large-scale undersea railway tunnel of 53.9 km long constructed at 240 m below sea level between Honshu and Hokkaido, surrounded by a sealing grout zone having a thickness three times greater than the tunnel radius, which was provided to counter against hydraulic pressure and inexhaustible water (Adachi and Tamura, 1978). Because of the importance of the services provided by the Seikan Tunnel, various

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measurement data have been accumulated on such factors as the convergence, amount of water inflow and earthquake motions for 20 years since the commencement of its service for conventional railway operations in 1988 (Tuchiya et al., 2005).

Focusing on the long-term tunnel measurement data, which have hitherto been rarely explored in past research, this paper organizes and analyzes the measurement data on the Seikan Tunnel and examines the mechanism of long-term behaviour of the undersea tunnel lining.

In specific terms, undersea tunnels may suffer from a reduction in seepage caused by the reduction in the permeability of the surrounding areas, as well as an increase in loads acting on the grout zone or lining, thereby experiencing the shrinking of cross-sections and lining troubles. To deal with these problems, this paper proposes a new methodology for evaluating the soundness of undersea tunnel linings, which has hitherto been rarely explored, and summarizes the evaluation results and future maintenance considerations for the Seikan Tunnel.

This chapter describes the results of measurements performed on the main tunnel, i.e., the amount of seepage water and convergence. In addition, some earthquake motion data obtained by a train operation control system are cited as reference information.

Seepage in the Main Tunnel
Seepage water is one of the most important issues in examining the maintenance of undersea tunnels. In the case of the Seikan Tunnel, seepage water should be monitored in terms of the amount, pressure and ingredient of seepage water to identify the conditions of surrounding rock mass and the soundness of the lining concrete. The seepage quantity is monitored with ultrasonic flow meters installed at intervals of approximately 2 km (Fig. 2), and so is the amount of pump discharge at Drainage Bases P1, P2 and P3.

Figure 3 shows the annual average seepage quantity per meter of the undersea portion derived from the measurement data taken by the ultrasonic flow meters. Figure 4 shows the seepage quantity in each year relative to that

![Fig. 2. Supersonic wave method's flow meter](image)

![Fig. 1. Longitudinal profile of the Seikan Tunnel](image)
in 1989, setting the latter at 100%. The “total seepage” shown in the figure is the same as the seepage quantity shown in Fig. 3. The description “P2 Pump only” given in the legend of Fig. 4 represents the pump discharge of P2 Drainage Base, which is dedicated to the collection of water from the underwater portion.

The total pump discharge of the tunnel decreased gradually by approximately 18%, from 26.22 m³/min in November 1988 to 21.4 m³/min in March 2005. The tunnel seepage has been on a decline, having been reduced by approximately 20 to 30 percent from the initial measurement.

**Measurement of Cross-sectional Displacements of the Main Tunnel**

Capable of directly showing structural changes, the measurement of cross-sectional displacements is one of the most reliable indicators to evaluate the soundness of a tunnel structure.

In the case of the Seikan Tunnel, quarterly measurements have been taken at four measurement points for each of the 77 cross-sections since March 1988.

Figure 5 shows an example of the measurement results for a water-containing fault zone at 16.8 km, which show relatively large displacements. Figure 6 summarizes the displacement measurements taken for the upper part of lining between the initial measurement and February 2004.

As shown in Fig. 6, 96% of the displacements of 77 sections are less than 3 mm, averaging out at 0.84 mm. It is also confirmed that the annual rate of change in displacements is less than 1 mm for all the sections between February 2004 and February 2005. Considering the fact that a general railway tunnel experiencing an annual rate of change in displacements greater than 1 mm requires
amount of seepage water
\( m^3/min \)

[Graph showing seepage water amounts from 1987/03 to 2003/03 with peaks at 2003/03, labeled Hokkaido Nansei Oki Earthquake.]

\[ P_1 + P_2 + P_3 \]

Total amount

Fig. 7. Amount of seepage water

strain (\( \mu \))

[Graph showing strain measurements from 1988/3 to 2005/3 with peaks labeled as a, b, c, d, e, f, g.]

Hokkaido Nansei Oki Earthquake

Fig. 8. Strain and temperature in the tunnel (21km 751m)
monitoring or other relevant remedies (Railway Technical Research Institute, 2007), the Seikan Tunnel is evaluated as being structurally sound.

Nonetheless, the tunnel has certain negative tendencies, as characterized by the continuing shrinking of cross-sections and increasing displacements though small, as shown in Fig. 5.

**Changes in Seepage Quantity and Lining Strain Caused by Earthquake**

Hokkaido has experienced four large earthquakes in the past (Table 1). The largest acceleration in the tunnel was observed when the Hokkaido Nansei Oki Earthquake occurred on July 12, 1993. It marked the maximum acceleration of 214 gals and 56 gals on the ground surface and in the undersea part of the tunnel, respectively. As having been confirmed in past earthquake data, the tunnel was found to have undergone smaller earthquake movements compared to the ground surface.

Figures 7 and 8 show measurement results recorded on the earthquake disaster prevention system. As seen from Fig. 7, the tunnel seepage underwent a temporal increase of 3.2 m³/min during the Hokkaido Nansei Oki Earthquake.

As shown in Fig. 8, strains in the tunnel lining concrete typically repeat annual cyclic changes ranging from 50 μ to 150 μ in accordance with changes in the annual average internal temperature ranging from 17 to 22 centigrade.

An exceptional behaviour was observed during the Hokkaido Nansei Oki Earthquake, where the circumferential strains showed an increase by approximately 300 μ in the tensile direction.

Measurement device of strains is set up to perceive momentary movement due to the earthquake, and the intended purpose is accomplished. But the long-term increase in strains doesn’t agree with the tendency in the increase in displacement, so it may be the accumulation of the error margin.

**EXAMINATION OF BEHAVIOUR MECHANISM**

**Procedure and Simulation Model**

As described in RESULTS OF LONG-TERM MEASUREMENTS, analysis of measurement results for the Seikan Tunnel confirmed that the seepage quantity is on a decline while the cross-sectional displacements are on the increase.

As the seepage and displacements are measured in different cross-sections, it is not feasible to simply discuss the results as if they had been obtained from a single cross-section. Nonetheless, the mechanism is examined here based on the following assumptions as to how the above phenomena are produced:

(a) The reduction in the tunnel seepage is caused by a decrease in the surrounding permeability. Two cases are assumed: a case where the permeability in the grout zone decreases and another where the deterioration of drainage performance at the back of the lining results in a reduction in the permeability there;

(b) The decrease in the surrounding permeability changes hydraulic pressure distributions around the tunnel, which increase the load acting around the tunnel;

(c) The load acting on the tunnel lining via rock mass is increased, and so are the displacements of the tunnel.

The evaluation procedure is shown in Fig. 9. First, using the permeability of the grout zone and that of the back of lining as parameters, the relationship between seepage and hydraulic pressure is simulated by seepage flow analysis. Next, assuming the change in hydraulic pressure derived from the analysis as an acting load, the deformation of the tunnel is simulated by deformation characteristics analysis.

The stress conditions of the lining are predicted by comparing the simulation results against the measured values to evaluate the soundness of the lining.

The simulation model is shown in Fig. 10. In the

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**Fig. 9. Flow of the examination**

**Fig. 10. Model of the simulation**
model, the seawater depth and the overburden are set at 140 m and 100 m, respectively, and the grout zone at a standard value of $3R$ ($R$: tunnel radius).

**Seepage Flow Analysis**

The relationship between seepage and hydraulic pressure is obtained by FEM-based seepage flow analysis. Analytical conditions are shown in Table 2. The analytical cases, where the permeabilities at the back of the lining and that in the grout zone are used as parameters, are shown in Table 3.

The central portion of the Seikan Tunnel is selected as the analytical target. A hydraulic pressure equivalent to a sea depth of 140 m is applied on the top of the model, and the permeability of rock mass is set at the standard value, i.e., $k = 1.0 \times 10^{-4}$ cm/s. Based on the past research (Kitamura, 1986), the permeability of the grout zone is set at 1/100 of that of rock mass, i.e., $k = 1.0 \times 10^{-6}$ cm/s. The permeability at the back of the lining is set at a considerably large value, i.e., $k = 1.0 \times 10^{-1}$ cm/s, assuming that the lining has the adequate drainage performance at its back.

For each of the above basic cases, a decrease in seepage is simulated by reducing the permeability in the grout zone and that in the lining. An example of hydraulic pressure distributions obtained from the seepage flow analysis is presented in Fig. 11. A higher hydraulic pressure is observed outside the grout zone, which becomes lower toward the tunnel side. A reduction in the permeability results in an increase in the hydraulic pressure around the tunnel.

**Determination of Acting Load**

Considering the fact that the concrete linings of a NATM tunnel are constructed after the settlement of displacements in shotcrete supports and that the Seikan Tunnel is not constructed in squeezing rock mass, it is assumed that the earth pressure does not increase after the completion of the structure. Therefore, the focus of analysis is limited to the changes in hydraulic pressure in accordance with a decrease in permeability.

Assuming that hydraulic pressure is borne by the shotcrete tunnel support and ground arching effect during excavation and construction of the lining, the load on the lining is assumed to be an increase in the hydraulic pressure brought about by a decrease in seepage.

In specific terms, seepage force distributions are derived from the difference between the hydraulic gradient during the lining construction and that with the decreasing seepage based on the hydraulic pressure distributions obtained in the seepage flow analysis as shown in Fig. 12. Because the seepage force shown in Fig. 12 acts on all points, the value obtained by integrating the seepage force with each element is designated as the load acting on each node in the analysis.

![Fig. 11. Hydraulic pressure distribution by the seepage flow analysis](image-url)
The load distributions with the decreased permeability in grout zone are shown in Fig. 13. As shown in the figure, the load acts on the entire grout zone where the permeability in the grout zone is reduced.

Note that the displacement and stress in the tunnel induced prior to lining construction are not directly related to the maintenance of the lining and thus excluded from the analysis.

### Deformation Characteristics Analysis

The deformation behaviour of the tunnel is derived from the load designated. The analytical condition per a tunnel longitudinal meter and the tunnel structure model are shown in Table 4 and Fig. 14, respectively. The lining of the Seikan Tunnel is plain concrete. The analysis is performed on the assumption that the corners of the lining, which are construction joints between successive pours, are pin joints as shown in the figure.

![Image](https://via.placeholder.com/150)

**Fig. 12. Summary of acting load**

**Fig. 13. Acting load distribution**

**Table 4. Analytical condition per a tunnel longitudinal meter**

<table>
<thead>
<tr>
<th>member</th>
<th>model</th>
<th>modulus of deformation $E$ [kN/mm²]</th>
<th>cross section $A$ [m²]</th>
<th>moment of inertia of area $I$ [m⁴]</th>
</tr>
</thead>
<tbody>
<tr>
<td>lining</td>
<td>beam</td>
<td>22</td>
<td>0.70</td>
<td>$2.858 \times 10^{-2}$</td>
</tr>
<tr>
<td>invert</td>
<td>beam</td>
<td>22</td>
<td>0.50</td>
<td>$1.042 \times 10^{-2}$</td>
</tr>
</tbody>
</table>

**Fig. 14. Structural tunnel model**

Figure 15 shows an example of displacements in the upper part of the lining and design member force of the lining obtained from the deformation characteristics analysis. The tunnel is deformed in a way that makes it shrink due to an increase in the load caused by a decrease in seepage, resulting in a considerable level of bending moment induced in the side walls.

Table 5 summarizes displacements in the upper part of lining and seepage quantity obtained in the seepage flow and deformation characteristics analyses. The current
Table 5. Result of analysis

<table>
<thead>
<tr>
<th>Case</th>
<th>the amount of seepage water [l/min/m]</th>
<th>displacement of upper line [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1-1</td>
<td>0.085</td>
<td>-0.80</td>
</tr>
<tr>
<td>Case 1-2</td>
<td>0.0086</td>
<td>-0.88</td>
</tr>
<tr>
<td>Case 1-3</td>
<td>0.0010</td>
<td>-0.92</td>
</tr>
<tr>
<td>Case 2-1</td>
<td>0.72</td>
<td>-0.02</td>
</tr>
<tr>
<td>Case 2-2</td>
<td>0.38</td>
<td>-0.46</td>
</tr>
<tr>
<td>Case 2-3</td>
<td>0.069</td>
<td>-1.44</td>
</tr>
<tr>
<td>Case 2-4</td>
<td>0.0075</td>
<td>-1.66</td>
</tr>
</tbody>
</table>

measured values for seepage quantity and displacements (0.11 l/min/m and 0.84 mm, respectively) are found to
be close to Case 1-1 or between Cases 2-2 and 2-3, indicating that the analytical results obtained here successfully
reproduce the present state of the lining.

SOUNDNESS EVALUATION FOR LINING CONCRETE

Evaluation by the Design Member Force Curve

As shown in Fig. 16, the design member force curve upon crack initiation is plotted to compare against the
analytical results. The curve plotted here was derived from the “Design Manual for Deformed Tunnel Remedies

Focusing on the red square that denotes Case 1 in the figure leads to the realization that the increase in design
member force is small where the permeability of grout zone is reduced from $10^{-7}$ cm/s (Case 1-1) to $10^{-9}$ cm/s
(Case 1-3). This indicates that the lining keeps its soundness where the reduction in seepage is caused by a
decrease in the permeability of grout zone.

As indicated by the circles in the figure, the design member force shows a larger increase where the permeability on the back of the lining is reduced from

$10^{-6}$ cm/s (Case 2-1) to $10^{-10}$ cm/s (Case 2-4). Therefore, where a decrease in seepage is caused by the decrease in
the permeability on the back of the lining, a considerable load is induced there, causing cracking and other forms of
deflection.

Judging from the current levels of displacements in the upper part of the lining and seepage, the design member
force corresponding to the measurement value is within the range presented in Fig. 16, which indicates that the
lining is in sound condition.

However, if a rapid decrease in the amount water is observed as in Cases 1-3 and 2-4, relevant measures such as
visual inspection and monitoring should be implemented. Relevant load reduction measures should also be
implemented if it is obvious that the back of the lining is subjected to loading.

If it assumes the discontinuity of stress between the lining concrete and the surrounding rock mass, it is possible
in Case 2 to cause the gap at the back of the lining. Two states are thought in such a case. One state is safe because
the gap is generated in the weak part of the rock mass and becomes water channel and the permeability of the tunnel
recovers. The other state is more dangerous because the hydraulic pressure is caused in the annexed gap and the
displacement of the lining increases rapidly. But it is too difficult to analyze the gap generation process, it is the
most important to do visual inspection if there is a rapid decrease in the amount water.

Development of “Crack Safety Index”

No past research has ever proposed a quantitative cracking index to be used in the maintenance of underwater
tunnels. Focusing on the convergence and seepage, this study proposes a method of quantitatively evaluating the
soundness of the undersea tunnel lining.

In specific terms, as shown in Fig. 17, the following “Crack Safety Index” is introduced to quantify the pre-
cracking allowance based on the analytical results and the design member force curve upon crack initiation:

$$\text{Crack Safety Index} = \frac{M_0}{M}$$

where,
**M**: Bending moment obtained from the analysis

\( M_c \): Bending moment derived from the design member force curve upon crack initiation.

It should be noted that there are a number of ways of determining the Crack Safety Index. The above index is determined to be on the most conservative side because an increase in the bending moment greatly contributes to crack initiation. By “the most conservative side,” it means the smallest index is adopted.

This index is designed for the initiation of cracks on the lining. The outbreak of cracks does not immediately mean the tunnel structure has become unstable; it usually requires more focused measurements and monitoring, as well as remedial measures if necessary.

**Fig. 16.** Design member force curve when crack forms and design member force

**Fig. 17.** Summary of Crack-safety-index

**Fig. 18.** Relation between the amount of water and the Crack-safety-index

Assuming that a reduction in seepage is caused solely by a reduction in permeability in the grout zone, the soundness of the lining that corresponds to the current measured value of seepage is represented by the position marked with circles in the figure. Here, the Crack Safety Index will be kept at an adequately high level even if the seepage quantity shows a further reduction, indicating that there is no risk of cracking or any other forms of deformation in the future.

On the other hand, assuming that a reduction in seepage is solely caused by a reduction in permeability at the back of the lining, the soundness of the lining that corresponds to the currently-measured seepage value is represented by the position marked with triangle in Fig. 18. Here, the Crack Safety Index will become smaller if seepage quantity shows a further decrease, indicating that there is a risk of cracking or other forms of deformation in the future.

**Correlation between Seepage Quantity and Crack Safety Index**

Figure 18 shows the relationship between seepage quantity and the Crack Safety Index.
Correlation between Displacements and Crack Safety Index

Figure 19 shows the relationship between displacements and the Crack Safety Index. Assuming that a reduction in seepage is solely caused by a reduction in permeability on the back of the lining, the Crack Safety Index will become smaller, indicating that there is a risk of cracking or other form of deformation in the future. The state of the lining that corresponds to the current displacement, which has been measured since 1988, is represented by the position marked with circles in Fig. 19. With no cracking observed, the lining is evaluated as in the sound condition.

Hydraulic Pressure in the Grout Zone and the Current State of the Lining

Figure 20 shows hydraulic pressure in the horizontal direction of the tunnel obtained in the seepage flow analysis.

Case 1: Decreasing permeability in the grouting zone

Fig. 20. Hydraulic pressure in the horizontal direction of the tunnel

Case 2: Decreasing permeability in the back of lining

Fig. 21. Results of hydraulic pressure measurement
Hydraulic pressure in the grout zone remains the same if a reduction in seepage is caused by a decrease in permeability in the grout zone. On the other hand, hydraulic pressure in the grout zone changes remarkably with a decrease in seepage, if a reduction in seepage is caused by a decrease in permeability at the back of the lining.

Figure 21 shows the results of measurements taken since 1999 for the hydraulic pressure in the service tunnel. Here, hydraulic pressure was measured through three boreholes created at a distance of 10 m, 15 m and 20 m from the sidewalls. As seen from the figure, the changes in hydraulic pressure in the grout zone is small, which indicates that the current state of the lining is close to Case 1 with the reduced permeability in the grout zone.

Change in the Crack Safety Index with Varied Levels of Ground Stiffness

In the analyses described above, the modulus of ground deformation is set at $E = 200$ MPa, assuming tuff in the relatively unfavourable condition. In the analysis here, it is set at $E = 100$ MPa and 50 MPa in order to examine changes in the Crack Safety Index with varied levels of ground stiffness. The results are shown in Figs. 22 and 23.

Where the level of stiffness is small, the Crack Safety Index is decreased, resulting in less than 1 where the modulus of deformation is $E = 100$ MPa or less.

Tunnels constructed in rock mass with a low level of stiffness are structurally less safe as they are susceptible to changes in permeability.

CONCLUSIONS

This paper focused on the long-term convergence measurement data on the Seikan Tunnel and examined the mechanism of its long-term behaviour. As a result, the following insights have been gained:

(a) Analysis of the results of long-term measurements for the Seikan Tunnel showed a continuous decrease in seepage and a reduction in the cross-sectional area.

(b) Simulations that combined seepage flow and deformation characteristic analyses were carried out for the Seikan Tunnel, which successfully reproduced the current soundness of the tunnel.

(c) The design member force curve upon crack initiation is implemented as an indicator and compared against the analytical values of design member force to evaluate the lining concrete of the undersea tunnel.

(d) Analysis of the Seikan Tunnel showed that the soundness of lining would be maintained if permeability in the grout zone was reduced, while its soundness may suffer if the drainage performance at the back of the lining had deteriorated.

(e) Comparison between the measurement results in the service tunnel and the simulation results in terms of changes in hydraulic pressure inside the grout zone indicated that the present state of tunnel lining is near Case 1 with the reduced permeability in the grout zone.

(f) Where the level of ground stiffness is low, a reduction in the permeability of surrounding ground tends to develop cracking in the lining. It is thus assumed that the lower the ground stiffness, the less structurally safe a tunnel becomes.

Based on the above results, an undersea tunnel maintenance method is proposed. Assumed here is an undersea tunnel like the Seikan Tunnel that has a grout zone and is subjected to high hydraulic pressure.

(a) Generally speaking, it is difficult to accurately evaluate the soundness of a tunnel in an inspection carried out after it has already undergone certain deformation. To this end, it is necessary to measure initial values including displacements immediately after the completion of construction and take regular convergence measurements, designating the appropriate intervals between the target cross-section areas.

(b) It is desirable to carry out the real-time monitoring of
seepage in an undersea tunnel, taking into account the importance of railway services for which the tunnel is used. For a long tunnel, it is necessary to take measurements on a greater number of points that are designated with constant intervals.

(c) It is effective to carry out simulations through seepage flow and deformation characteristics analyses based on measurement results to confirm the impacts of hydraulic pressure on undersea tunnels. It is particularly important to quantify the risk of an increase in displacements and a decrease in seepage through application of the concept of "Crack Safety Index" as a safety factor to the crack-initiating state of the lining.

(d) It is vital not to allow hydraulic pressure to act on the back of the lining of an undersea tunnel. Therefore, the maintenance of drain functions through regular cleaning of such facilities as drain ditches and conducting tubes plays a vital role in ordinary maintenance activities.

(e) Measuring seepage pressure at the back of the lining is crucial to confirm the impacts of seepage on an undersea tunnel.

(f) A rapid reduction in the amount of seepage is dropped rapidly and an increase in the cross-section area indicates the presence of a load working on the back of the lining. Therefore, relevant load-reduction measures should be implemented, such as through provision of drain holes.

The insights gained through the research on the Seikan Tunnel are useful for examining the impacts of seepage in the maintenance of other undersea tunnels. However, the method presented here is based on a simple two-dimensional model, leaving the examination of three-dimensional behaviour of hydraulic pressure and seepage as one of the future research issues.

With the Seikan Tunnel still undergoing changes in seepage and displacements, continued measurement efforts are necessary to ensure the safety of railway operation and soundness of the tunnel structure.

REFERENCES


