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CASE STUDY OF A BEHAVIOR MONITORING IN A FILL DAM FOR ACCURATE AND LONG TERM MEASUREMENT

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1. INTRODUCTION

Though Majimegawa dam is a small scale earth fill dam, the dam site had some geological difficulties on the strength and the groutability because most of foundations are composed of weathered rocks and sands. To overcome these difficulties, Yamaguchi Prefecture who is the project body adopted an advanced monitoring system.

This monitoring system achieved the epoch making success with a long term reliability and higher accuracy to catch some behaviors on displacement, deformation and pore water pressure in the dam body, using GPS (Global Positioning System) and other equipments. Further, it shows the potential to meet various requirements in the dam daily and emergency management.

It is important to monitor the behavior of a dam body continuously at real time for the dam safety management. In this paper, the authors report the background of this challenge, the performance of this new monitoring system and the behavior analysis in the first impounding of Majimegawa Dam.

(*) *ETUDE DE CAS PORTANT SUR LA SURVEILLANCE DU COMPORTEMENT DANS UN BARRAGE EN REMBLAI POUR DES MESURES PRÉCISES ET À LONG TERME*

2. OUTLINE OF MAJIMEGAWA DAM

2.1. Purpose and Dimensions of Majimegawa Dam

The Majimegawa dam was completed in 2009 as an indispensable facility on the river improvement master-plan by Yamaguchi Prefecture, for the purpose of flood control and maintenance of the environmental river function, which are located in the west of Japan. Though dimensions and geology of the dam are shown in Table 1, it has achieved some important technical innovations on the advanced monitoring.

Table 1
Dimensions of Majimegawa dam
Dimensions et géologie du barrage de Majimegawa

Site	Ube city, Yamaguchi prefecture		
Completion of project	2009 fiscal year	Terms of works	Dec.2002 - Jun.2007
Dam type	Central cored earth fill dam		
Height of dam body	Main dam: 21.9m, Sub dam: 20.4m		
Length of dam body	Main dam: 209.5m, Sub dam: 145.0m		
Volume of dam body	Main dam: $152x10^3m^3$, Sub dam: $89.3x10^3m^3$		
Volume of reservoir	842 m^3 x 10^3m^3		
Geology of foundation	Granite, the surface of which is rather weathered but tight. Sand of granite is called Masa which means genuine sand.		
Permeability of foundation	Most of area is less than 5 Lugeon, partially more than 10 Lugeon in abutments.		
material of embankment	Earth fill: Masa sand and granite stone around the dam site Core: soil and stone of granite and clayey schist		

2.2. Structural Features of Majimegawa Dam

The almost foundations in the dam site consist of Masa sands which are made of granites by weathering actions, and the abutment are covered by weathered granite rocks. The Masa sand has some disadvantages because of its less strength and less groutability compared to normal dam foundations.

Then, some structural designs like below was decided.

1) The earth fill dam type with a gentle slope (upper slope 1:3.3) was selected to construct the body on the weak foundation.
2) The centered core and core trench at the core base was adopted to stop the water from the reservoir, without the curtain grouting, because water is cut by impermeability of the Masa sand.
3) The chimney drain was placed along the back of the core to lower the pore water pressure strongly.
4) The inspection gallery was avoided because of undesirable motions in an earthquake owing to the short stiffness of the foundation.

During the construction works, some structural improvements were implemented like below.

1) The elevation of the horizontal drain was raised up by about five meters to enable the free flow without pumping up. (see Fig. 3)
2) The additional embankment on the lower slope was implemented by using the surplus soil. It contributed to beatification by planting, earthquake

resistance, and seepage reduction by backside water pressure. (see Fig. 3)

3) The shallow grouting was added in the main dam abutments and the sub dam river bed where many cracks/joints in rocks were found (see Fig. 2).
4) The foundation under the spillway base was strengthened by the artificial abutment of concrete.
5) The materials of drains were purchased to keep the high quality.

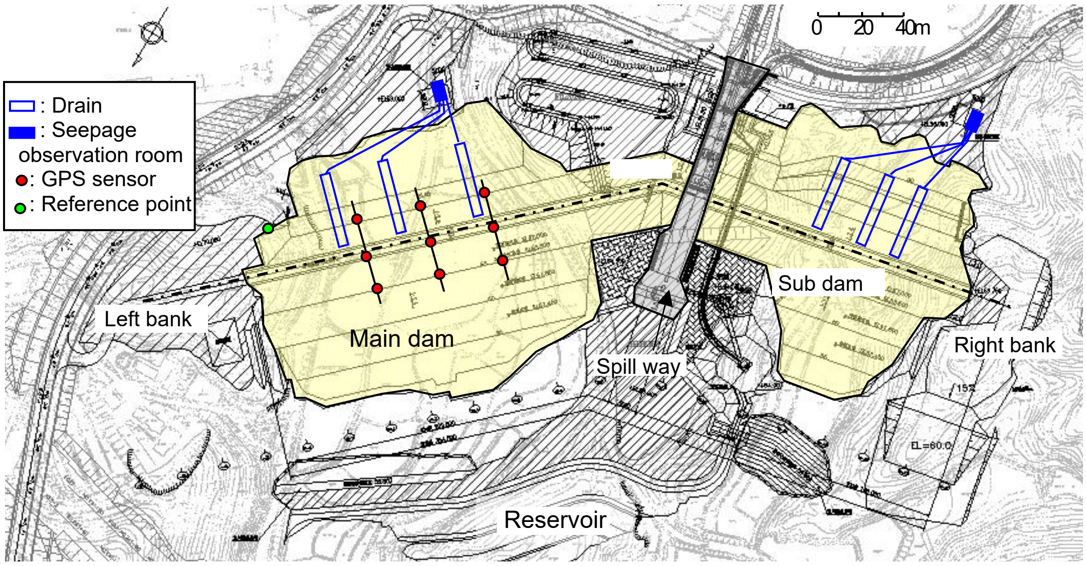


Fig. 1
Plan of Majimegawa dam and the observation points
Plan du barrage de Majimegawa et les points d'observation

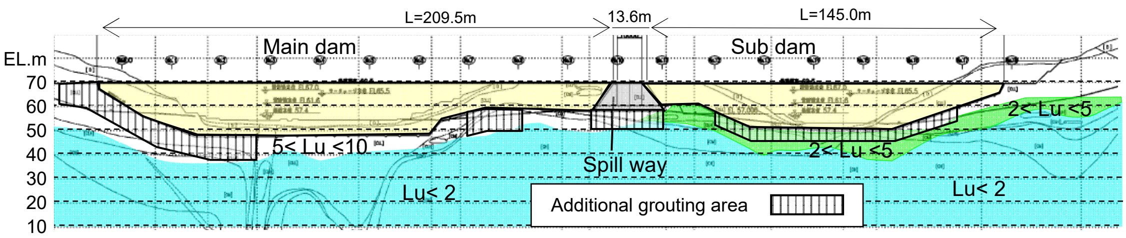


Fig. 2
Upstream view of Majimegawa dam
Vue vers l'amont du barrage de Majimegawa

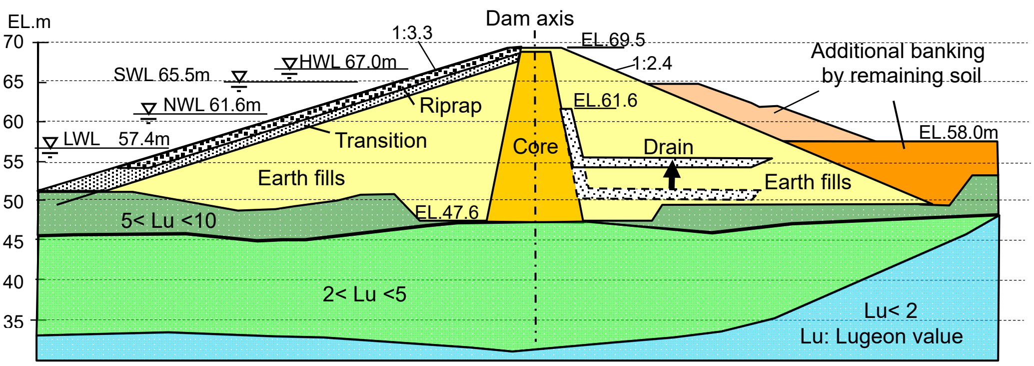
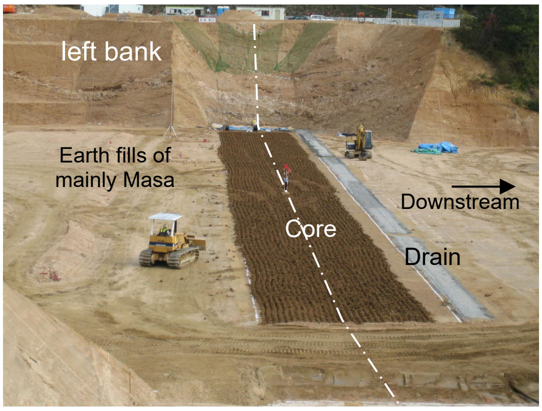


Fig. 3
Cross section of the main dam and permeability in the foundation
Coupe transversale du barrage principal et perméabilité dans les fondations

2.3. Construction Works of Majimegawa Dam

Embankment works in the main dam and sub dam of Majimegawa Dam started at Aug. 25 2004 and finished at Jul. 7 2006. Further, the first impounding implemented from Jan. 15 2006 to Mar.12 2009.

The photographs of Fig. 4 show the situation in the construction such as weathered granite, Masa sand, embankment works, drain works, and so on.



a) Main dam view from the right bank

b) Weathered granite rock at the left bank

c) Core, materials are Masa sand and granite stone

d) Drain, materials are purchased gravel and sand

e) Base rock (granite) near the Spill way

f) Top of the sub dam, ripraps and rocks

Fig. 4
Construction situation of Majimegawa dam (Nov. 16 2005)
Etat des travaux de construction du barrage de Majimegawa (16 nov. 2005)

3. ADVANCED MONITORING SYSTEM IN MAJIMEGAWA DAM

3.1. Necessity of Accurate and Long term Behavior Monitoring

In Majimegawa dam, it is strongly requested to implement some effective methods instead of no curtain grouting and no inspection gallery, owing to its difficulties to improve the impermeability and less strength of the foundation. The most actual and reliable methods to satisfy this requirement is to confirm several safety factors of the dam such as impermeability of the foundation and displacement of the dam body for a long term. Thus, the project office adopted an advanced monitoring system to measure behaviors of the dam accurately with a long term continuity, which are mainly consist of vibrating wire type piezometers, GPS sensors, and so on. Additionally, the both devices were the first case of a full scale and long term observation in Japan.

3.2. Installed Devices for Observation of Dam Body and Foundation

Several kinds of observation devices were installed in the dam body and its foundation, which were piezometers, GPS sensors, multi level settlement meters, the bed rock displacement meters, and so on (see Table 2 and Fig. 5).

Table 2
List of installed observation devices in Majimegawa dam
Liste des dispositifs d'observation installés dans le barrage de Majimegawa

Device/ Equipment (object)	Number in the main dam	Number in the sub dam	Sign in Fig. 5
Piezometer (pore pressure)	Vibrating Wire 19 set	Vibrating Wire 17 set	
GPS sensor (displacement)	9 set	-	
Multi level settlement meter (settlement in the core)	Sliding-Resistance 4 set (max 5 level)	Sliding-Resistance 2 set (max 5 level)	
Bed rock meter (displacements in the foundation)	Sliding-Resistance 1 set	Sliding-Resistance 1 set	
Boring well (ground water level)	6 wells	6 wells	
Seepage observation facility	3 areas to 1 observation room	3 areas to 1 ob-servation room	

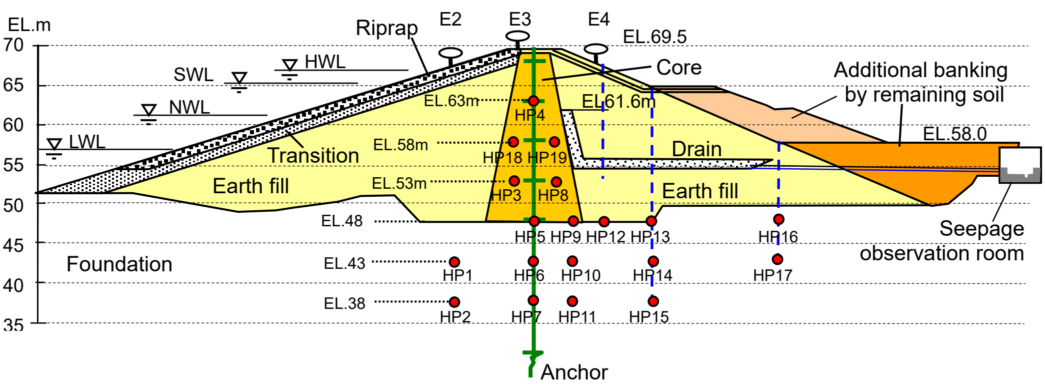


Fig. 5
Cross-section and installed device positions in the main dam
Coupe transversale du barrage principal et position des dispositifs installés dans le barrage

3.2. Installation of Vibrating Wire Type Piezometers

The piezometers were installed by the three methods below.

1) Setting the meters in the boring hole of the foundation
2) Placing the meters on the surface of the foundation
3) Placing the meters on the roller compacted surface of the core zone

The pressure signals are picked up by the vibrating wire type sensor. This type sensor is superior in the long term reliability and the workability compared to the conventional type such as the strain gauge type and the differential transformer type, because its conversion mechanism is simpler, it is less sensitive to the electric condition and its cable is slenderer and connectable. Fig. 6 shows the installation of vibrating wire type piezometers in Majimegawa dam.

Setting in the core

Setting in the foundation

Fig. 6

Installation of vibrating wire piezometers in Majimegawa dam

Installation des piézomètres à fil vibrant dans le barrage de Majimegawa

3.3. Installation of Multi Level Settlement Meter

A multi level settlement meter (5 layers) was set at the same point as E3 in Fig. 5, the elevations of which are EL=48, 53, 58, 63m and 68m. The settlement signals are converted to sliding-resistances, and are picked up by the differential transformer type sensor. Fig. 7 shows the setting situations in Majimegawa dam.

Setting in the core (Nov. 16 2005)

Setting on the base rock

Fig.7

Installation of multi level settlement meter in Majimegawa Dam

Installation de tassomètres à multiple niveaux dans le barrage de Majimegawa

3.4. Installation of GPS Sensors on the Main Dam

Nine GPS sensors were installed by three measuring lines parallel to the dam axis which were the upstream slope line (G2, E2 and C2), the dam top line (G3, E3 and C3), and the downstream slope line (G4, E4 and C4) of the main dam, so that the most of the dam surface can be covered in field (see Fig. 5). In addition, the measurement of the downstream line (G4, E4 and C4) started from Apr. 1 2007, and the other lines started Sep. 7 2007.

Concerning the coordinate directions, X-axis is set in the up-downstream direction (upstream is positive), Y-axis is set in the left-right abutment direction (left is positive), and H axis is set in the vertical direction (upheaval is positive).

Fig. 8 and 9 shows the installed situation of the GPS sensors.

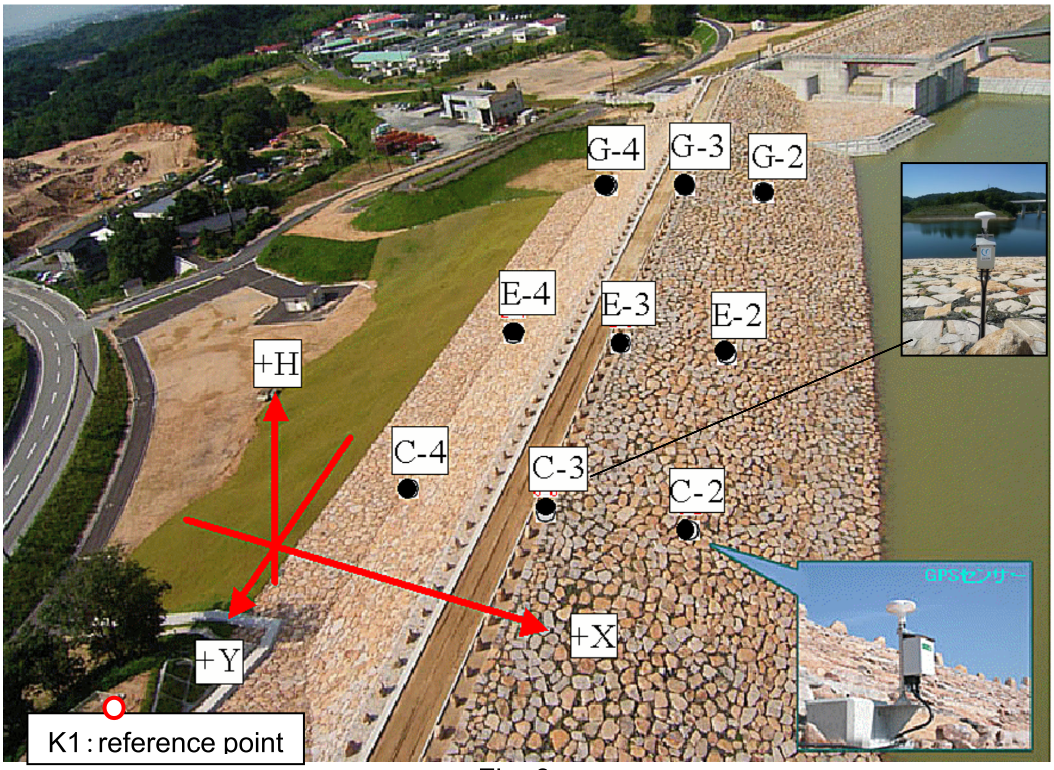


Fig. 8
Installed position of the GPS sensors
Emplacements des capteurs GPS installés sur le site

Downstream point (E2) | Dam top point (E3) | Upstream point (E2)

Fig. 9
Installed situation of the GPS sensors (E2, E3 and E4)
Positionnement des capteurs GPS installés sur le site (E2, E3 et E4)

3.5. Observation of Pore Water Pressure during the Construction Works

Fig.10 shows the pore pressure data by piezometers in the sub dam from 2005.8 to 2006.11. The pore pressures in the foundation were stable around the under ground water level. On the other hand, though the pore pressures in the core increased rapidly with the progress of the embankment, these over-pressures disappeared steadily by the drain placed behind the core zone.

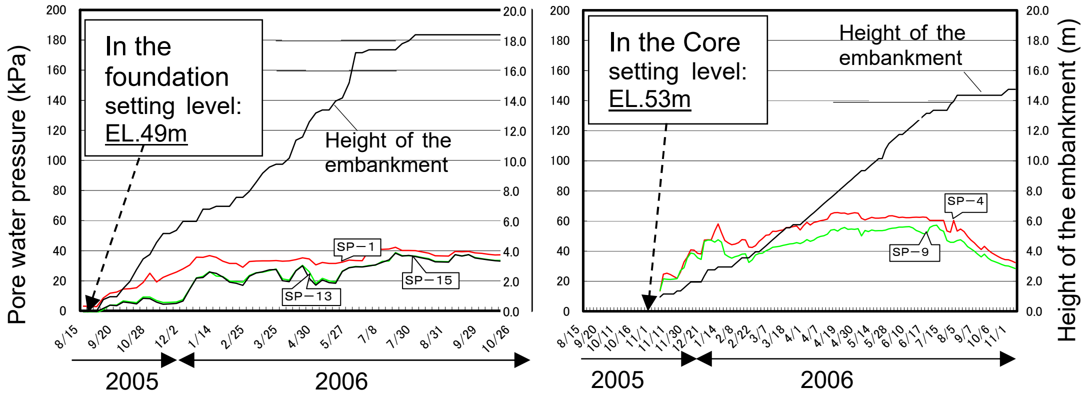


Fig.10
Pore water pressure progress during the sub dam construction
Progressin de la pression interstitielle de l'eau durant la construction du barrage secondaire

3.6. The Settlement Observation in the Core since the Construction Works

Fig.11 shows the data of the multi level settlement meter from Jul. 2005 to Sep. 2009. The settlement values of 5 levels in the core increased rapidly with the progress of the embankment, these values became constant after the embankment works. At the present, though the progress of settlements mostly finished, HVL-5 only near the dam top is slightly subsiding.

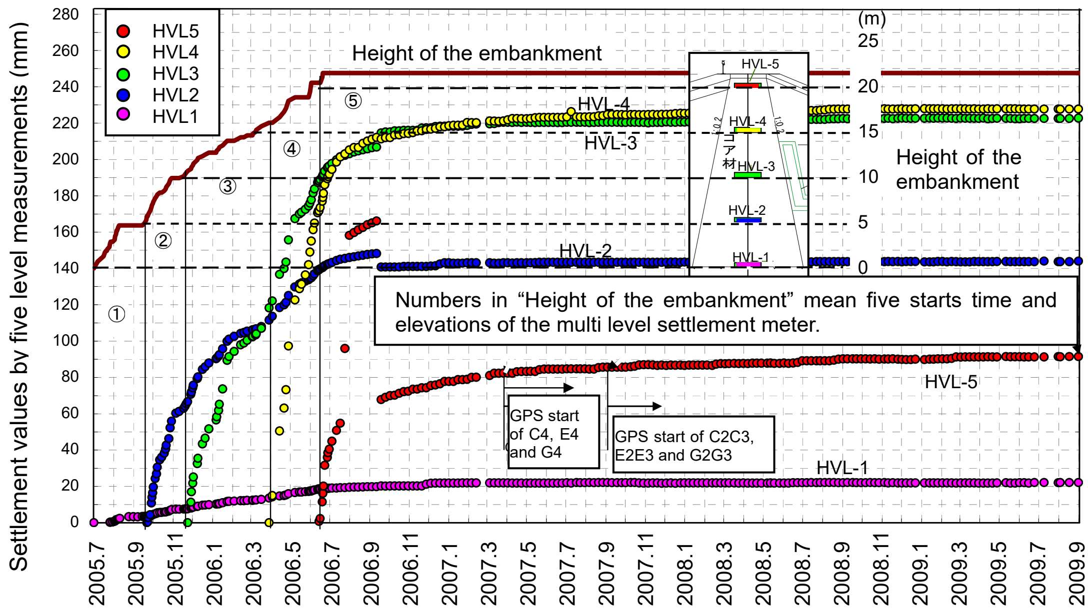


Fig.11
Settlement progress in the main dam by five levels (Jan. 2005 – Sep. 2009)
Progression du tassement dans le barrage principal selon cinq niveaux

4. BEHAVIOR ANALYSIS IN THE FIRST IMPOUNDING

4.1. Relation between Seepage Quantity and Reservoir Water Level

Fig.12 shows the seepage quantity in the main dam from 2007 to 2009. The seepage quantity basically corresponds to the reservoir water level, but it is also influenced by the precipitation. The seepage quantity is big in order of the left, right and center area, because the left area foundation has some crack zones and the widest catchment area connected to a mountain. The total maximum 95 L/min is not so much as a fill dam, and there is no serious sign on the dam safety.

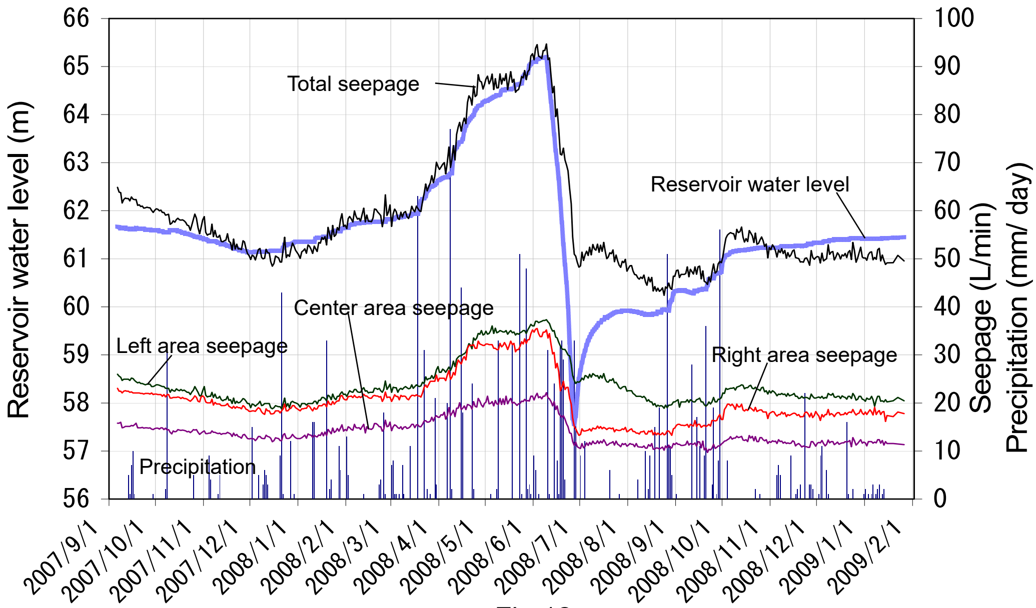


Fig.12

Relation between seepage quantity and water level (Sep. 2007 – Feb. 2009)

Relation entre la quantité d'infiltration d'eau et le niveau d'eau du réservoir (2007 – 2009)

4.2 Relation between Pore Water Pressure and Reservoir Water Level

Fig.13 shows the pore water pressures of 19 sets in the main dam from Mar. 2007 to Sep. 2009. We can find several trends like below.

1) In the whole, the pressures correspond to the reservoir water level.

2) In particular, the pressures in the foundation sharply respond to the reservoir water level, but downstream pressures (HP13-HP17) are small and stable enough. It means the foundation is evenly near impermeable, and there is no serious seepage route to affect the reservoir function.

3) The pressures in the core insensitively respond to the reservoir water level, because the reservoir water in case of rising is late to transfer by the impermeability of the core, and the excess power water pressures in the dropping water level easily remain inside of the core.

4) The downstream pressures are strongly reduced by the drains. It means the drains were quite effective, considering their purposes to improve the embankment workability and to improve the sliding safety of the dam body by increasing the actual vertical load.

5) All of vibrating wire type piezometers have worked well since 2005. It proves

that this type meter is quite suitable for a long term observation.

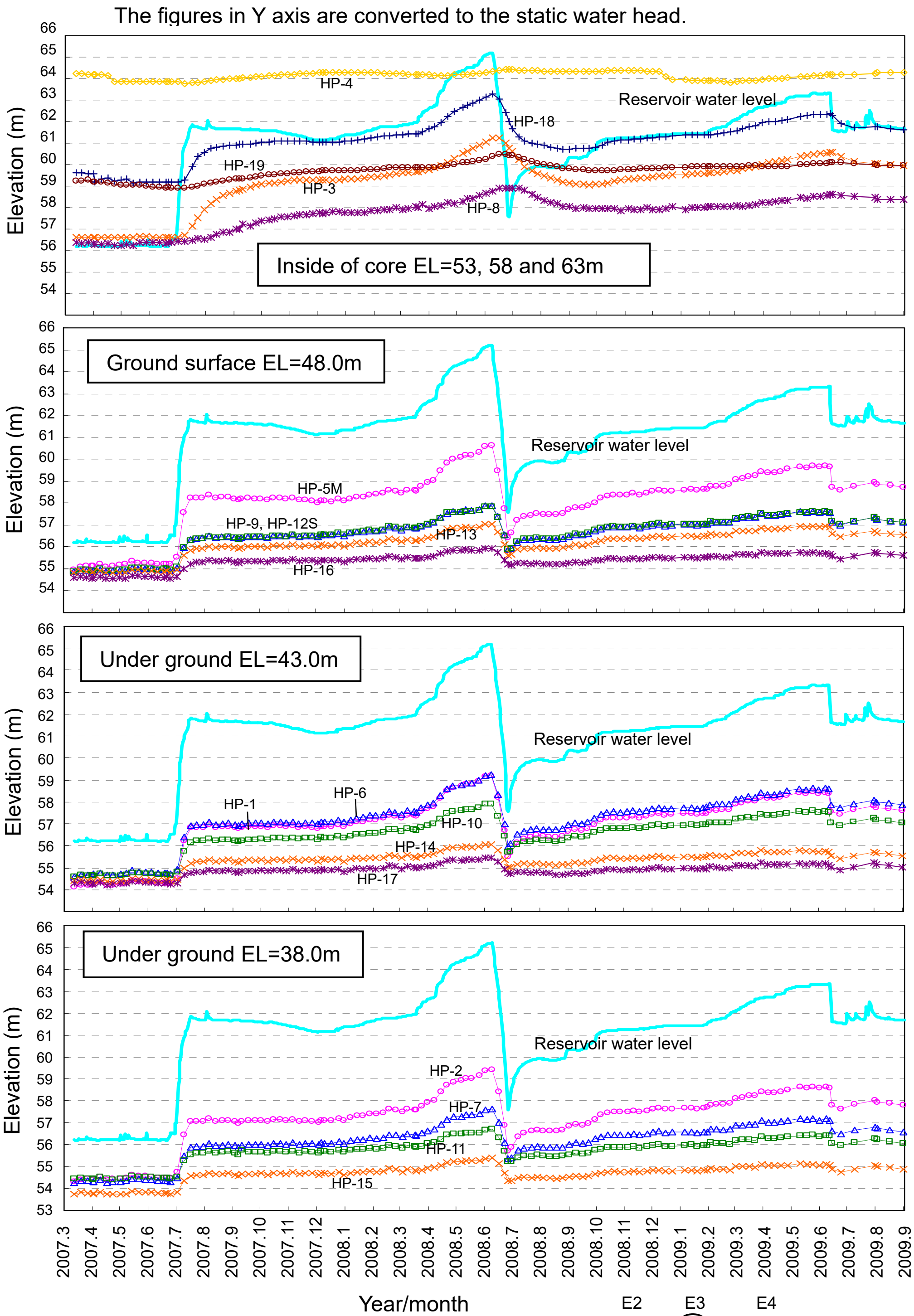
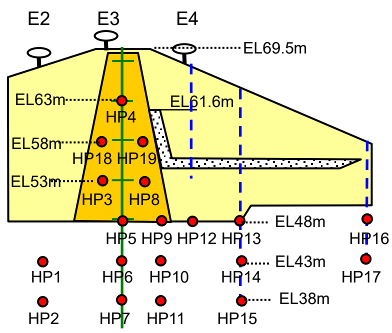


Fig. 13
Data of pore water pressures in the main dam and reservoir water levels (from Mar. 2007 to Sep. 2009)
Données concernant les pressions interstitielles et les niveaux d'eau dans le réservoir du barrage



4.3. Relation between GPS Displacement and Reservoir Water Level

Fig.14 shows the relation between the water level and the GPS values.

1) Firstly, the displacements in up-downstream of E2, E3 and E4 are closely connected to the water level. They move to downstream when the water level is rising, and they return to upstream when the water level is dropping. E4 has been always affected to move upstream by drains.
2) The displacements in left-right direction of E2, E3 and E4 are increasing to the left very slightly, when the water level is rising. This motion might be caused by the consolidation by a drain placed in near side of the left.
3) The motions in vertical direction are very closely connected to the water level and the settlement of the dam body. E2 and E4 upheave when the water level is rising, and they subside when the water level is dropping. But, E3 has consistently subsided with the settlement of the dam body.

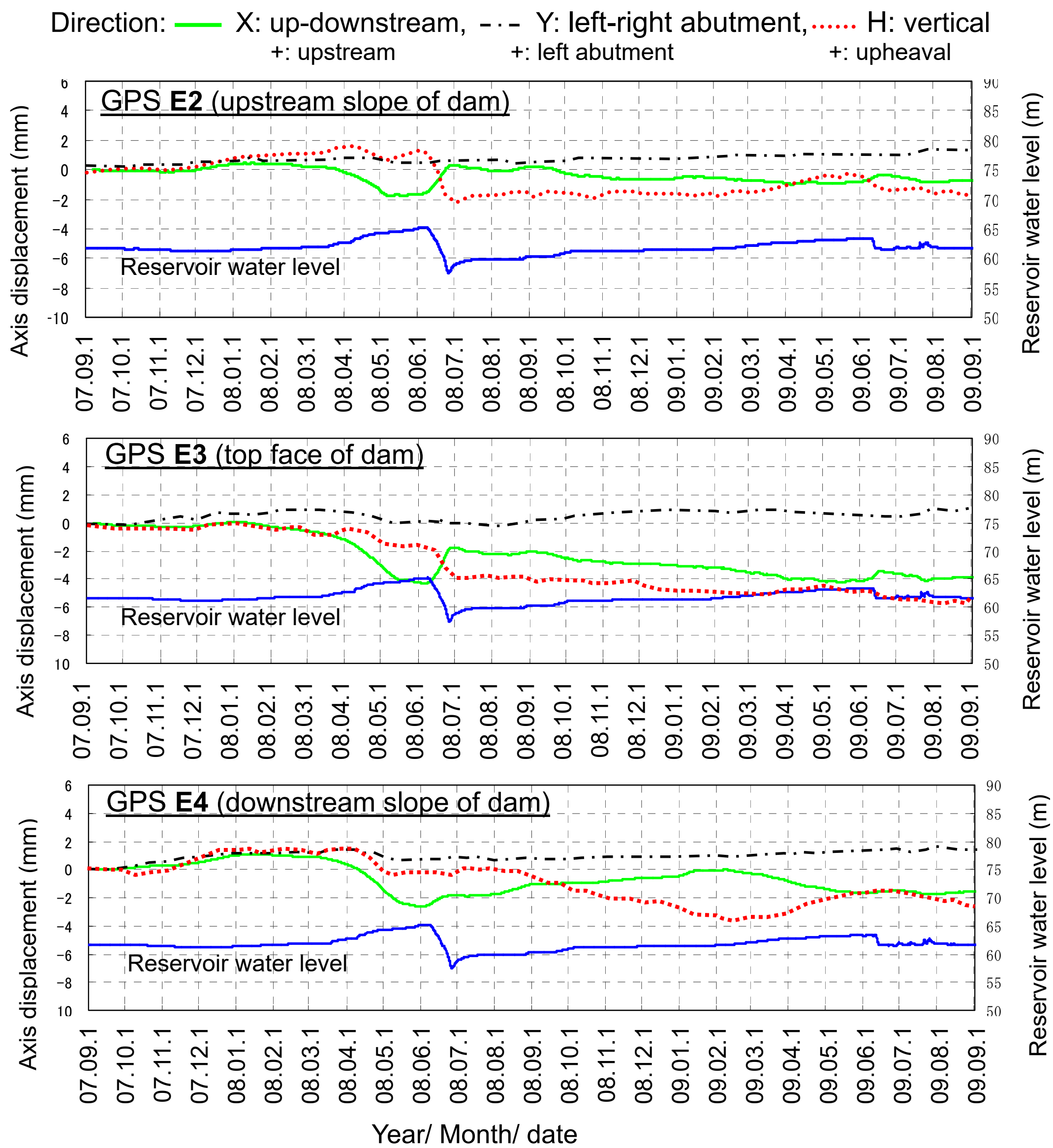


Fig. 14

Relation between GPS displacement and reservoir water level

Relation entre les déplacements GPS et le niveau d'eau dans le réservoir du barrage

4.4. Relation between Pore Water Pressure and GPS Displacement

Fig.15 shows the progress of pore water pressures and displacement vectors of E2, E3 and E4 in up-downstream by five divided terms from Sep. 2007 to Sep. 2009. The phreatic lines are estimated by the pore water pressures and the reservoir water level. The relations among these factors are as follows.

1) Term 1: The water level slightly decreases by 0.51 m. E3 slightly moves to down and downstream, but E4 slightly moves to up and upstream.
2) Term 2: The water level increases by 4.05 m. E2 moves to up and downstream, but E3, E 4 moves to down and downstream.
3) Term 3: The water level decreases by 7.64 m. E2, E3 moves to down and upstream, but E4 moves to up and upstream.
4) Term 4: The water increases by 5.77 m. E2 moves to up and downstream, E3 moves to down and downstream, and E4 moves to down and upstream.
5) Term 5: The water level decreases by 1.66 m. E2, E3 moves to downstream, but E4 moves to upstream.

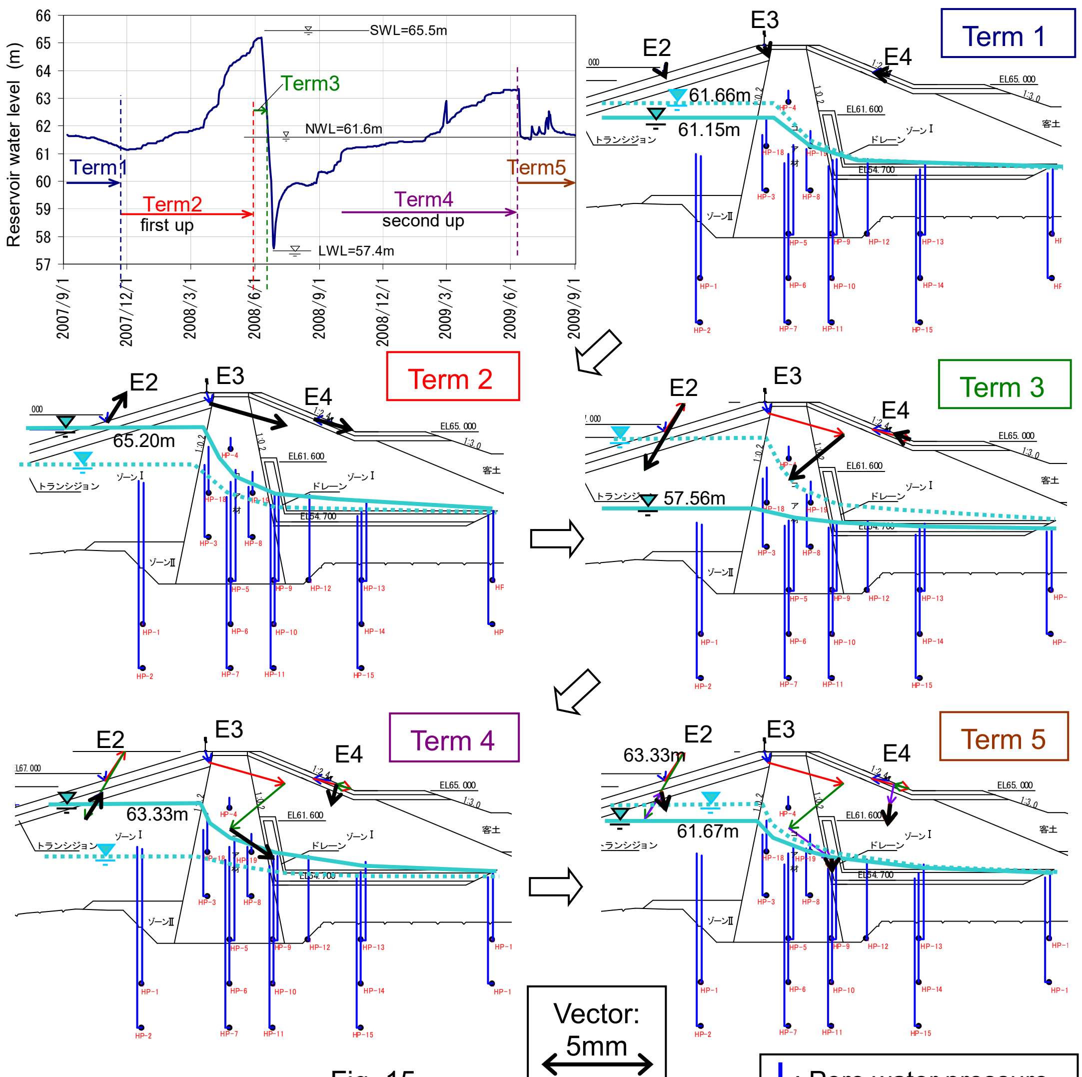


Fig. 15
Relation between water level and GPS displacement
Relation entre le niveau d'eau dans le réservoir et les déplacements GPS

| : Pore water pressure (Static water head)
: Seepage line
:GPS displacement

Concerning to the above, the displacements in up-downstream are gradually reduced by the repeated up-down of water level. Fig.16 shows GPS values are closely connected to the horizontal load which calculated by the water head differences in the core zone. Its trend shows the elastic-plasticity of the core, and it becomes more elastic after repeated loads of water pressures.

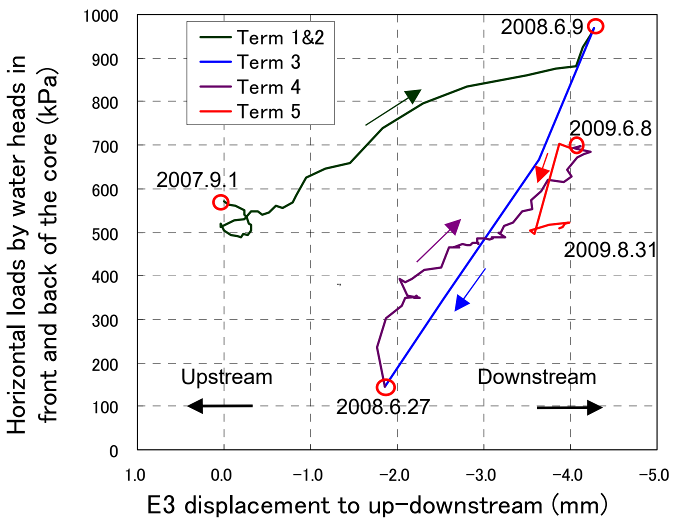


Fig. 16
Relation between horizontal load and GPS E3 displacement
Relation entre la charge horizontale et les déplacements GPS

4.6. Relation between Settlement and GPS Vertical Displacement

Fig.17 shows the relation between settlement data and vertical displacements at E3 with the effect of GPS observation like below.

1) On the whole, settlement values are affected by the reservoir water level, but a convergence tendency is found with consolidation by the embankment.
2) The values of multi level settlement meters just correspond to the GPS values. The both values are very close.
3) GPS sensors capture the minute behaviors of the dam body by accuracy as same as the settlement meter.
4) Thus, it is clear that the GPS values are reliable enough, and it can be measured by mm accuracy.

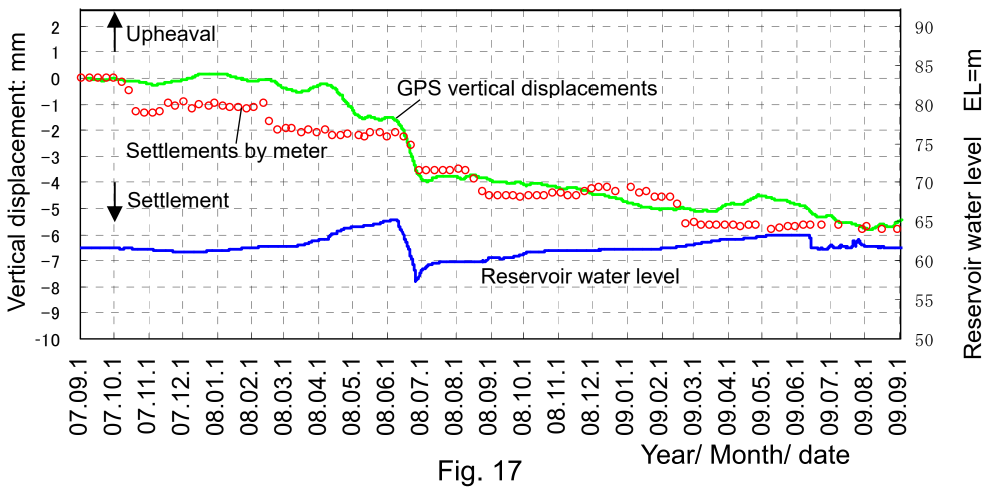


Fig. 17
Relation between settlement data and GPS E3 vertical displacement
Relation entre les données concernant le tassement et les déplacements GPS verticaux

4.7. Trend Model for Improving Accuracy of GPS

The GPS continuous displacement monitoring system adopted here was originally developed by the second author and his associates as an Industry-Academia collaborative project [1-3]. It is widely used not only in dam [4-6], but also in various geotechnical projects related to monitoring landslides, cut slopes, open quarries, ground subsidence, tunnels, foundations, and so on in Japan [7].

The system is illustrated in Fig.18. Receivers (sensors) are set on a measurement point and the reference point, and they are connected to a control box into which a computer, a data memory, and a network device have been installed. The data emitted from the satellites are transferred to the control box through cables. The server computer, which is located at an office away from the measurement area, controls the entire system to acquire the data from the control box and to analyze them in order to obtain the displacements at all the measurement points.

The standard deviations (STD) of the measurements using conventional GPS receivers are 5-10 mm and 10-20 mm for horizontal and vertical directions, respectively. Therefore, the accuracy of the conventional GPS is not sufficient for precise monitoring. In order to improve the accuracy, the trend model was applied to the continuously monitored results [1]. The trend model is one of the smoothing techniques for estimating the real values from scattered data (Fig.19). It is composed of a system equation and an observation equation, as follows:

$$\Delta^k u_n = v_n \qquad\qquad y_n = u_n + w_n$$

where u_n represents the estimates for the exact values of the displacements and y_n is the measured displacement. The measurement interval is Δt and subscript n denotes progressing time t ($t = n\Delta t$) □ Δ is the operator for the finite difference ($\Delta u_n = u_n - u_{n-1}$) and Δ^k means the rank “k” difference. The above equation is a kind of probability finite difference equation for rank k. v_n and w_n are white noises with an average value of 0, an STD of τ, and an observation error with an STD of σ.

The trend model can yield good estimates for exact displacements from scattered data obtained from the GPS monitoring system. Through experiments and practical applications, it was proven that the system can detect displacements of 1-2 mm and displacement velocities of 0.1 mm/day [1, 7].

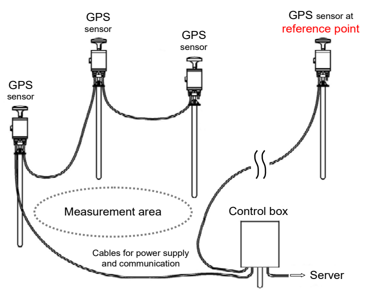


Fig. 18
GPS displacement monitoring system
Système de surveillance des déplacements GPS

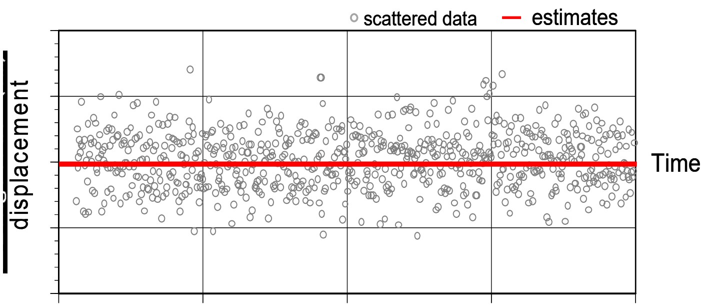


Fig. 19
Estimation of exact displacements from scattered data
Estimation des déplacements exacts à partir des données exactes

5. CONCLUSIONS

This paper described an example of monitoring the behavior of a dam body continuously for the dam safety management.

The key findings are as follows;

1. Precise monitoring the mechanical behavior of a rock fill dam with vibrating wire piezometers, multi level settlement meter and GPS displacement monitoring system was successfully conducted.

2. The relationships among the reservoir water level, the seepage quantity, the pore water pressures and settlements in the dam body, and three dimensional displacements of the dam were discussed from measurement results for assessing the stability of the dam.

3. The pore water pressures in both of the dam embankment and foundation could be measured very clearly. They corresponded to the change of the reservoir water level.

4. The GPS displacement monitoring system could detect three dimensional behavior of the exterior deformation of the dam with millimeter accuracy in real time. It was proven that the accuracy almost equals to the precise multi level settlement meter even in the vertical displacement.

5. The directions of three dimensional displacement vectors almost coincide with the change of the reservoir water level and the phreatic line estimated from the distribution of the pore water pressures.

6. On the whole, when the water level is increasing, the dam body (mainly core) moves to downstream. Inversely, when the water level is decreasing, the dam body (mainly core zone) moves to upstream. It seems these behaviors are caused mainly by the imbalance of water pressure to the core zone, which is caused by the impermeability of the core and the consolidation by the drains.

7. The GPS displacement monitoring system and the vibrating wire type piezometers are recommended to monitor the behavior of dams as high accurate instruments available for long term monitoring.

8. The relation between the estimated horizontal loads and the GPS displacements shows the process that the elastic-plasticity of the dam body becomes more elastic after repeated loads of water pressures.

9. It is quite significant on the dam safety management to connect behaviors of a fill dam comprehensively to various acting factors such as permeability of its body and foundation, weights, consolidation by gravity, draining effect, up lift effect, phreatic line, water level, additional banking and so on.

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SUMMARY

It is important to monitor the behavior of a dam body continuously at real time for the dam safety management. Since Majimegawa Dam Project confronted to follow up the foundation problem caused by the short of strength and groutability of Masa sand (weathered granite) which is the main geology, it adopted an advanced monitoring system using accurate and durable devices such as the GPS (Global Positioning System) sensors, vibrating wire type piezometers, and so on.

As a result, in the first impounding, the new monitoring system achieved the brilliant success to prove the safety of the dam, getting the long term reliability of the observation data. The GPS monitoring enabled to grasp the displacements of the dam body with the higher accuracy and durability compared to the conventional measuring. The water pressure monitoring and the seepage observation enabled to grasp the behavior of the water flow in the foundation and dam body more exactly. Further, the integral analysis of these data enabled to show the relation of the load situation and displacements reasonably.

RÉSUMÉ

Il est important de surveiller continuellement le comportement du corps du barrage en temps réel afin d'assurer la bonne gestion des conditions de sécurité du barrage. Le Projet du barrage de Majimegawa ayant été confronté au suivi du problème des fondations causés par le manque de résistance et de possibilités d'injection du sable de Masa (granit désagrégé) qui constitue le principal élément géologique, on a adopté un système de surveillance sophistiqué de pointe utilisant divers dispositifs précis et durables tels que des capteurs GPS (système de positionnement global), des piézomètres du type à fil vibrant, etc.

Il en a résulté, dans le premier endiguement, que le nouveau système de surveillance a brillamment réussi à prouver la sécurité du barrage au vu de la fiabilité à long terme des données d'observation. La surveillance au moyen du système de positionnement global a permis de saisir les déplacements du corps du barrage avec une plus grande précision et durabilité comparé aux données obtenues au moyen des mesures conventionnelles. La surveillance de la pression de l'eau et l'observation de l'infiltration a permis de mieux comprendre et avec une plus grande exactitude le comportement de l'écoulement de l'eau dans les fondations et le corps du barrage avec une plus grande exactitude. En outre, l'analyse intégrale de ces données a permis de montrer raisonablement la relation de la situation de charge et des déplacements.