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STRUCTURAL SAFETY MONITORING FOR TAI TAM UPPER RESERVOIR DAM

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ABSTRACT

Water Supplies Department (WSD) of HKSAR Government set up the Reservoir Safety Section in 1970s to ensure the safe operation of reservoirs through routine surveillance and monitoring with the help of appropriate instrumentation installed at dams and reservoirs. Tai Tam Upper Reservoir was one of the oldest reservoirs built on the Hong Kong Island in the period between 1883 and 1888. The gravity dam forming the reservoir did not have any instrumentation for monitoring of structural performance when it was built. This paper describes the safety surveillance and monitoring carried out at this dam by the Reservoir Safety Section, and explains how results of monitoring were used in the assessment of dam stability and planning for safety improvement works.

At Tai Tam Upper Reservoir Dam, monitoring of seepage through the dam during the 1990s revealed relatively weak and permeable foundation materials at the right and left abutments of the dam. Remedial works comprised a series of foundation grouting for sealing leaks and strengthening of the dam foundation.

KEYWORDS

Gravity dam, v-notch, piezometer

INTRODUCTION

WSD is currently operating and maintaining 29 impounding reservoirs (including irrigation reservoirs), 185 fresh water service reservoirs and 58 salt water service reservoirs. Storage of raw water in impounding reservoirs and treated water in service reservoirs are essential to ensure reliable water supply in Hong Kong. Any uncontrolled release of water from these reservoirs will result in not only the loss of precious water resources, but also the possible severe flood problems in areas downstream of the reservoirs. WSD set up the Reservoir Safety Section in 1970s to ensure the safe operation of reservoirs through routine surveillance and monitoring with the help of appropriate instrumentation installed at dams and reservoirs. A senior engineer headed the Section with four surveillance teams comprising reservoir safety engineer and technical staff. WSD adopts the spirit of the U.K. Reservoirs Act (1975) and arranges regular safety surveillance inspections of reservoirs in three levels. The top level of surveillance inspections is carried out by a qualified civil engineer appointed to the All Reservoirs Panel under the Act engaged by WSD through consultancy agreements. Such independent inspections are usually carried out at least once in ten years for each reservoir. Two consultancy agreements are arranged for the inspection of reservoirs in Hong Kong. One agreement is for the inspection of impounding reservoirs and service reservoirs with capacities larger than 25,000 m^3, and the other is for the inspection of service reservoirs with capacities smaller than 25,000 m^3. The second level of safety surveillance inspections is carried out by the in-house reservoir safety engineers. The frequencies of inspections are as recommended by the All Reservoirs Panel Engineers (ARPEs), usually twice a year to once per three years. The third level of inspections is carried out by the technical staff of the surveillance teams who also observe and collect instrumentation data during their inspections. These inspections are normally on monthly basis.

Tai Tam Upper Reservoir was one of the oldest reservoirs built on the Hong Kong Island in the period between 1883 and 1888. The gravity dam forming the reservoir did not have any instrumentation for monitoring of structural performance when it was built. This paper describes the safety surveillance and monitoring carried out at the dam by the Reservoir Safety Section, and explains how results of monitoring were used in the assessment of dam stability and planning for safety improvement works.

DAM MONITORING - A GENERAL INTRODUCTION

In simple terms, monitoring means the observation and deduction of the performance and behavioural trends of a dam and associated structures by means of the securitization of various data collected and recorded by measuring devices. Surveillance refers to the continuing examination of the condition of a dam and its associated structures and the review of operation, maintenance and monitoring procedures and results in order to determine whether a hazardous trend is developing or appears likely to develop.

Dams can broadly be classified into two main types according to their construction, viz. masonry or concrete masonry gravity dams, and earth or rock fill embankment dams. The design of each dam is unique. The instrumentation system design, therefore, requires careful consideration of the specific design and identified problems of the dam, and the site-specific geotechnical conditions present at the dam and along the reservoir rim. The following types of monitoring are commonly found in a lot of major dams:

Movement and Deformation Monitoring

For all the dams in Hong Kong, and many dams in the world, movement and settlement of the dam crest and deflection of the dam body are monitored by land survey methods on a regular basis, e.g. twice a year or more frequently.

An inclinometer can also be used to measure any lateral deflections of the dam body through the depth of a borehole formed in the dam.

On a smaller scale, local minor movements, such as widening of a crack, can often be monitored by the installation of a tell-tale or an extensometer across a crack.

Pore Pressure Monitoring

In many dams, piezometers or ground water observation wells have been installed in the dam body and its foundation. Monitoring of the piezometers and observation wells provides pore pressure data which are essential for the assessment of the stability of the dam. In some earth embankment dams where piezometers installed in the dam body respond quickly to changes in reservoir storage levels, the piezometers readings can be logged and analysed automatically by a computer system which will issue dam distress alerts to dam safety staff if anomalies are detected.

Piezometers installed in concrete gravity dams usually respond relatively slowly to changes in reservoir storage levels than those installed in earth embankment dams due to the lower permeability of concrete. Piezometer monitoring in gravity dams is useful in picturing the pore pressure distribution within the body of the dam which is an essential piece of information for assessing dam stability.

Seepage Monitoring

No dam is absolutely watertight. Water may seep through the dam body, joints between adjacent panels of the dam wall, the dam foundation, and the abutments on either side of the dam. Seepage can be collected in a chamber installed at a suitable location of the drainage path. A vertical steel plate with a v-notch (usually of 60^o, 90^o or 120^o) is installed at the downstream end of the seepage collection chamber. The seepage rate is indicated by the depth of flow measured at the v-notch. Correlating the measured rate of seepage to rainfall and reservoir storage level will tell the behaviour and the performance of the dam. Abnormal increasing trend in the seepage rate may indicate development of new seepage paths or the dam body may have become more permeable because of the development of internal erosion. The seepage flow may appear muddy if internal erosion is taking place, as the seepage flow is transporting earth materials out of the dam body. Therefore, a turbidity meter can be used to measure the quality of the seepage flow. Sometimes an increase in seepage rate may be accompanied by a higher piezometer readings.

TAI TAM UPPER RESERVOIR

Tai Tam Upper Reservoir was constructed in 1883. It is the second oldest reservoir in Hong Kong. The reservoir is impounded by a masonry-faced concrete gravity dam. This historic structure of the dam was declared in 2009 as one of the monuments among waterwork heritages in Hong Kong. The dam was classified as Grade 1 monument. The dam was originally constructed to a crest level of 151.9m PD with the spillway crest at 151.3m PD. The original design incorporated provisions for raising and in 1897 the dam was raised by 3.84 m and the spillway crest level was raised to 154.3m PD. The spillway crest however was subsequently lowered in 1936 to its present level of 153.4m PD. The current height of the dam is 42 m, and the length of the dam at the crest level is 151 m. Figure 1 shows the downstream view of the dam.

There has been a long history of leakage from the dam. In 1977, the ARPE recommended a further lowering of the sill level by 1.16 m in order to improve stability of the dam and the provisions for dealing with flood flows as well as the leakage through the dam, and the right abutment foundation. The overflow spillway is independent of the dam and situated some 150m from the right abutment.

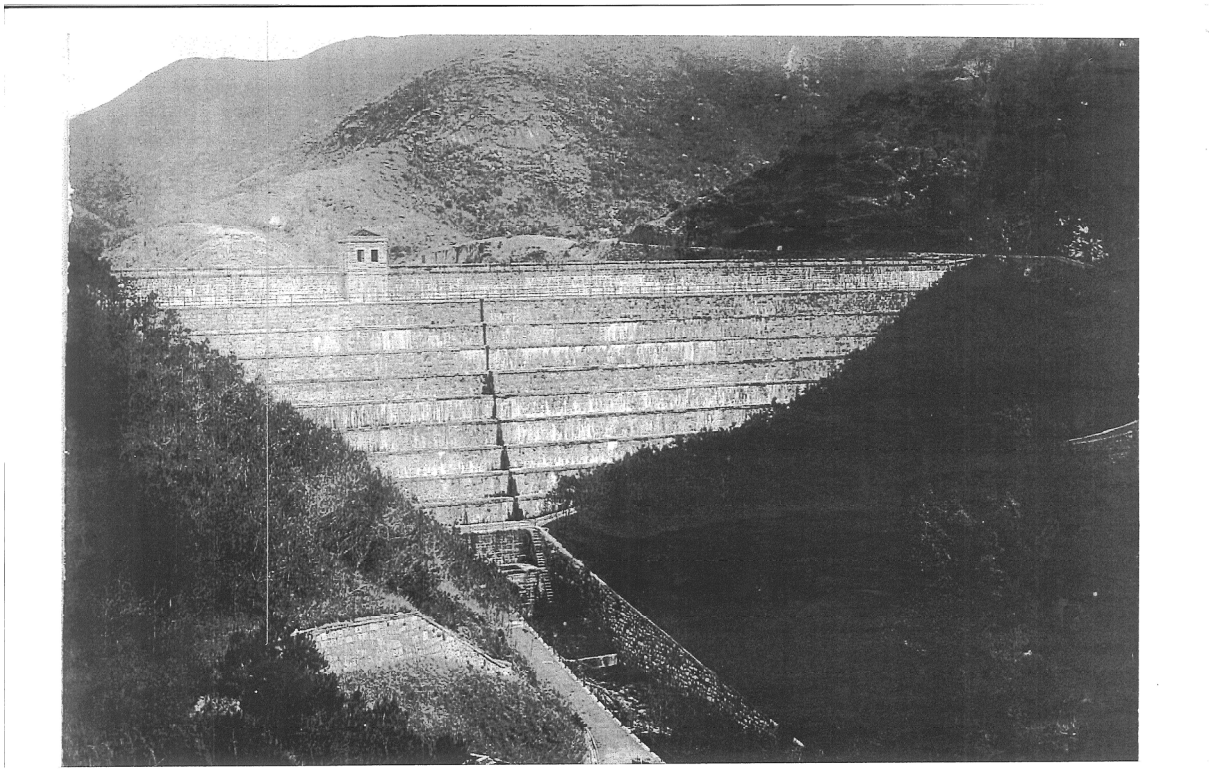

Figure 1. View from downstream side of Tai Tam Upper Reservoir Dam

From 1977 to 1987, inspection of Tai Tam Upper Reservoir recorded leakage through the dam. The ARPE responsible for the safety inspection in 1987 recommended sealing the upstream face of the dam by pressure grouting the joints in the masonry face to reduce seepage through the dam. Before the grouting was carried out, individually monitoring of the seepage flows from all of the berm drains in the downstream right abutment was necessary. Figure 2a shows the schematic arrangement of the seepage collection system for monitoring seepage flows from the berm drains. There are six flow monitoring chambers, named B3R to B8R, along the right abutment groin, and five flow monitoring chambers, named B4L to B8L, along the left abutment groin. Figure 2b shows a close-up view of chamber B5R and the v-notch plate for measuring flow rate. The remedial works in 1991 also included grouting of the right abutment foundation, and part of the dam body near the right abutment.

The subsequent seepage flow data collected by the flow monitoring system were used to assess the effectiveness of the grouting works in 1991, and further grouting works between 1991 and 1993. Before the implementation of the remedial works, major flows were collected in flow chambers B4R, B5R and B6R along the right abutment groin. Figure 3 shows a plot of the total seepage flow measured by the three flow chambers against the reservoir water level. The plot shows the correlation between the measured total flow from these three chambers and the reservoir level, and indicated significant reduction in seepage immediately after each stage of grouting. Borehole investigations during the 1991 grouting works revealed a completely weathered granite zone at the right abutment foundation close to flow chambers B4R, B5R and B6R which might be the cause of high seepage through the right abutment. The investigations also revealed that the materials in the dam body were porous as the core of the dam body contained large rock (granite) displacers. Zone of richer concrete was close to but not immediately adjacent to the upstream masonry face. Review of the seepage flow monitoring data indicated that leakage was mainly through the right abutment, despite that the dam body was porous.

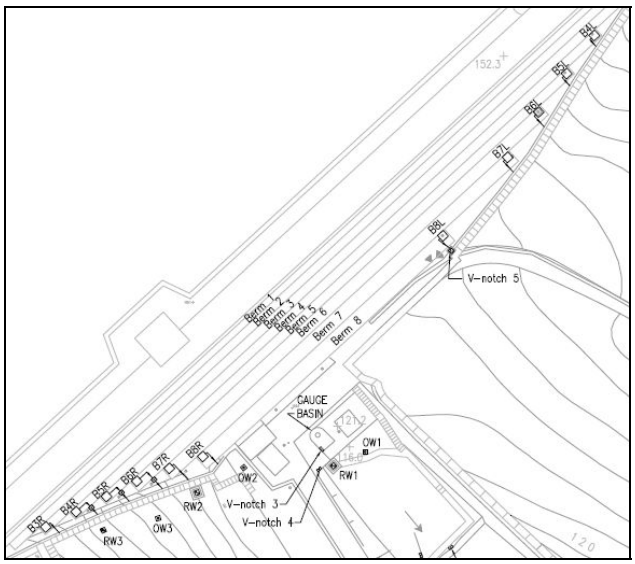

Figure 2a. Schematic arrangement of seepage flow monitoring system at Tai Tam Upper Reservoir Dam.

Figure 2b. Close-up view of flow chamber B5R at the right abutment groin.

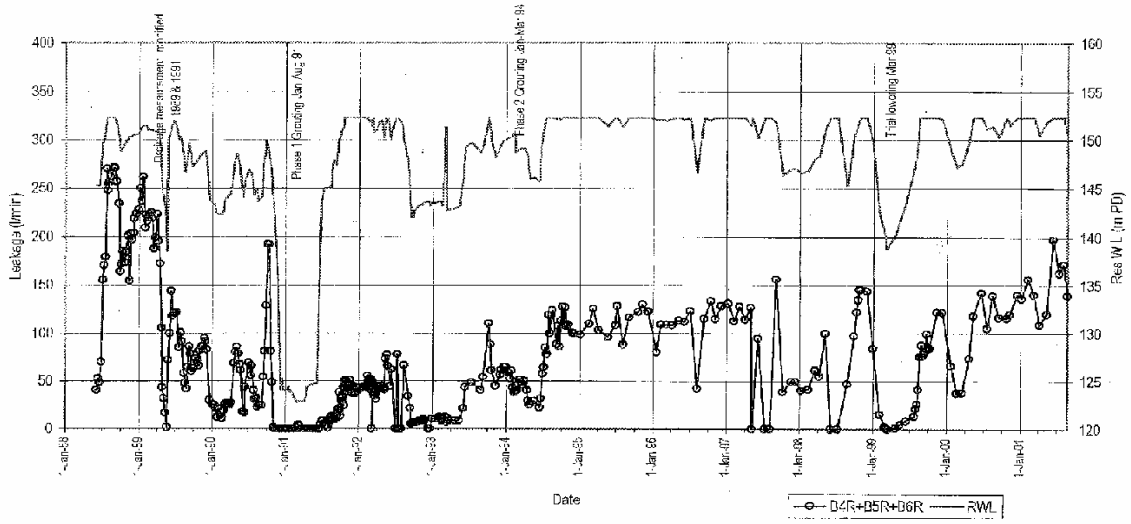

Figure 3. Plot of total seepage from flow chambers B4R, B5R and B6R versus reservoir level (Gallacher 1998)

Further site inspections in Dec. 1998 and a follow up visit in 1999 were carried out to inspect leakage at the dam. Discharge at the right abutment drains was strong. Material deposited in the silt chambers consists of sand with some gravel and a few traces of grout. This confirmed that erosion was taking place in the right abutment

foundation. Samples of eroded material were selected for examination and sieve analysis, and the soil was found to be 9 to 30% gravel, 57 to 69% sand, and 7 to 34% silt and clay. The ARPE recommended to carry out investigation and remedial works to the upper part of the Right abutment to further reduce and stabilise leakage and to prevent any more erosion of the foundation in 2002. Construction of a multi-line grout curtain was decided. The grouting procedures are shown in Figure 4.

Grouting lines A and C are the upstream and downstream lines respectively and line B is the central line of the 3 line grout curtain over the main part of the curtain. The drilling and grouting plant were located on the platform below walkway on the dam crest. Ordinary Portland Cement, Superfine Portland Cement, Ultrafine Portland Cement and chemical grout were used as the grouting materials.

The final impoundment test showed the total discharge from the drains at the berms on the downstream face of the dam with the reservoir at top water level was 26l/min, which was about 10-15% of the original discharge.

A final site inspection was made by ARPE in 2006. Berm drainage results for June 2006 were reviewed with the reservoir level about 0.6m below top water level and it was found that total discharge from the berm drains had decreased by about another 50%, indicating further self healing over a period of about 9 months.

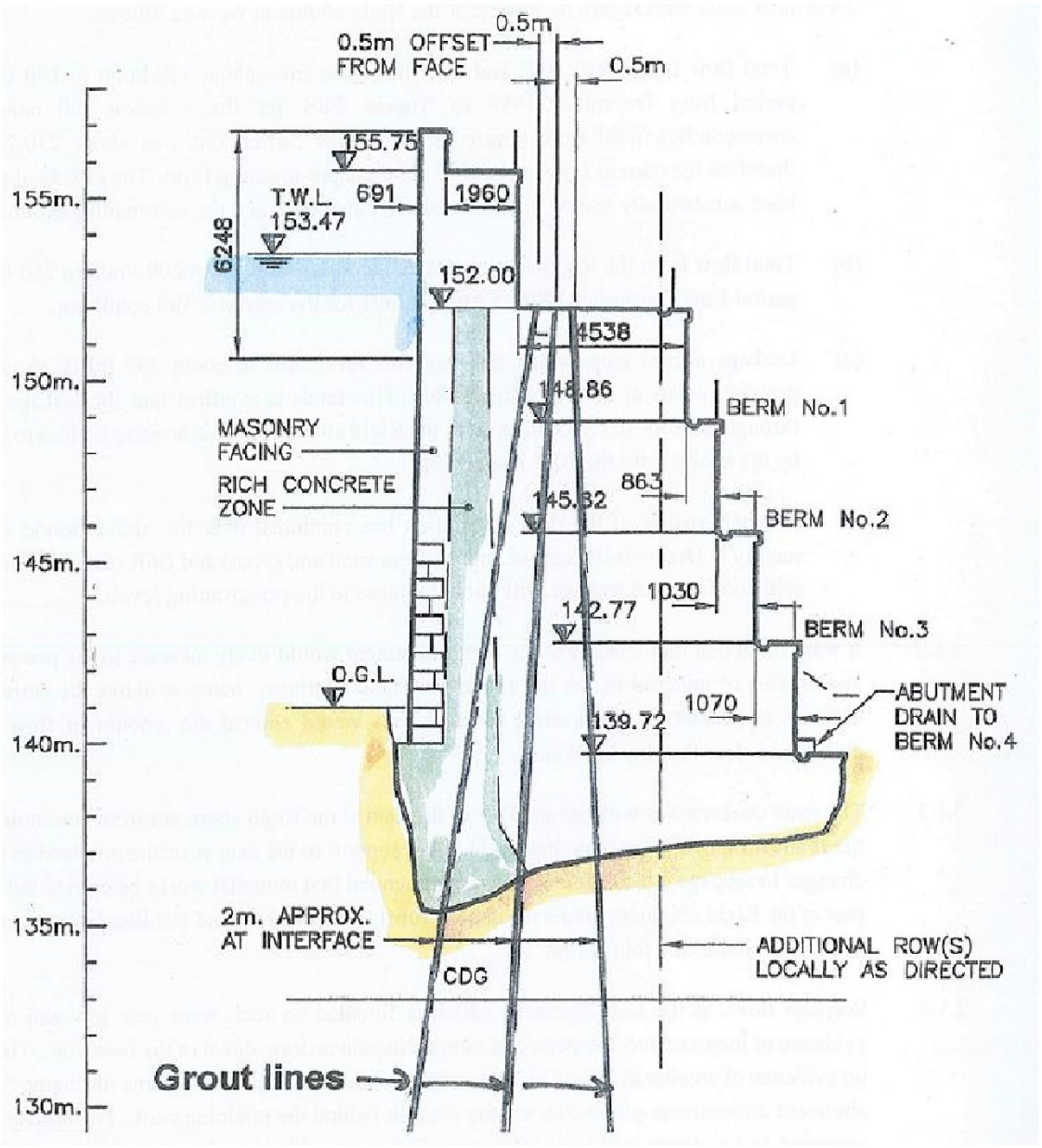

Figure 4. Typical section of grouting at right abutment

CONTINUAL INSPECTION AND MONITORING

The inspection, monitoring and maintenance cycle for the safety of Tai Tam Upper Reservoir will continue. WSD will make every effort to preserve this monument.

Replacement of piezometers at the dam of Tai Tam Upper Reservoir will be carried out in the near future. WSD will have a chance to examine and test the concrete cores of the dam. The characteristics of the concrete within the dam body will be used to carry out further analysis of the dam safety. This reservoir is scheduled for the next ARPE inspection in 2018.

CONCLUSIONS

This Paper introduces the role of the Reservoir Safety Section of WSD in ensuring safe operation of the Department's impounding reservoirs and service reservoirs through routine monitoring and safety surveillance of these facilities. The paper provides a brief introduction of the various types of instrumentation for the structural monitoring of reservoir dams. Seepage monitoring at Tai Tam Upper Reservoir Dam is discussed, in particular, to illustrate the rationales in the analysis of the dam monitoring data and the application of such monitoring data in gauging the effectiveness of dam safety improvement works.

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