Sustainability-Based Construction of the Restoration Projects for the Guguan Hydropower Station

Taiyi Liu¹, Pohan Chen² and Chou Nelson N.S.³

¹ New Asia Construction and Development Corporation, Taiwan
tlytpe@ms9.hinet.net
² Civil Engineering Department, National Taiwan University, Taiwan
pohanchen@ntu.edu.tw
³ Civil Engineering Department, National Taiwan University, Taiwan
nchou1031@gmail.com

Abstract. In Taiwan, the Dajia River is one of the most important rivers that provides hydroelectric energy. A couple of well-operated hydropower stations have been placed in different sections of this river for several decades. The 921 earthquake that hit central Taiwan in 2000 and Typhoon Toraji that attacked this area in 2001 caused severe damage to almost all hydropower stations. To continue to provide sufficient power for the public, the restoration of these power stations is necessary. Taiwan Power Company (Taipower) was responsible for the restoration projects. The Guguan hydropower station, which could provide 212.8 MW power, is one of the most damaged power stations. The Guguan power station restoration project, executed by the New Asia Construction and Development Corporation (NA Corp.), was started in April 2002. During the project, a series of typhoons and heavy storms attacked central Taiwan between 2004 and 2007 (especially Typhoon Mindulle in 2004). Consequently, the restoration work was greatly hindered; in particular, there was massive groundwater leakage from all external walls of the tunnel and powerhouse structures. The maximum leakage of groundwater was up to 84 tons/min. This situation not only caused extreme difficulty that interrupted the restoration work but also made the construction site a dangerous environment to continue restoration or future operation. In addition, the construction facilities were damaged, resulting in suspension of the restoration work. For safety construction of the restoration work, a series of temporary protection structures/platforms and a large quantity of grouting work had been performed. This power station was well restored and engaged in commercial operation in October 2008. In this paper, the detailed working procedures of the safety construction methods are presented.

Keywords. Sustainable safety, Sustainability, Guguan hydropower station, 921 earthquakes, Typhoon Taraji, Typhoon Mindulle, Taipower, New Asia Corp.

1. Introduction
On September 21, 2000 at 01:45 AM, a 7.3-magnitude earthquake hit Jiji town, located in central Taiwan. Hundreds of buildings collapsed, thousands of human lives were lost, and damage spread across almost all of Taiwan. Large quantities of infrastructure were destroyed during the main shock and aftershocks, including several hydropower stations along the Dajia River.

Five hydropower stations, namely, Techi, Chinslan, Guguan, Tienlung, and Maan, are located along the Dajia River and have been engaged in commercial operation for several decades. Figures 1 and 2 show the plan view and vertical profile of those power stations, respectively.
The Guguan and Chinshan hydropower stations were the most damaged stations during the 921 earthquake and Typhoon Toraji in 2001. Both of these two restoration projects were bided by Taipower and performed by NA Corp. The height of the riverbed of the Dajia River increased up to 10 meters due to rockfall caused by the 921 main shock and aftershocks. In addition, the riverbed increased a further 9 meters due to debris flow during Typhoon Toraji. All equipment in the power station had been flooded following these two disasters. The elevation of the riverbed is considerably higher than the outlet of the tailrace tunnel, resulting in complete destruction of the power station and shutting down of power generation. Figure 3 shows the flooding situation of the power station after the 921 earthquake and Typhoon Toraji.
Figure 3. Flooding situation of the Guguan power station after the 921 earthquake and Typhoon Toraji. Reference: Sinotech journal No.108, 2010 (Figure representation by Tai-Yi Liu)

Figure 4. Site conditions before and after the 921 earthquake and Typhoon Toraji. Figure 4 shows photos of the site conditions before and after the 921 earthquake and Typhoon Toraji. Reference: Sinotech journal No.108, 2010 (Figure representation by Tai-Yi Liu)
2. Project Performance Framework

2.1. Framework of Project Performance

The issue of sustainability of infrastructure construction projects has become increasingly important in recent years. Some key indicators that impact sustainability, such as carbon emission reduction, energy saving, environment protection, ecology reservation, safety, and landscape, have gained attention. In this study, the authors focus on the safety during and after construction of the restoration work. Figure 5 shows the framework of the project performance.

![Figure 5. Framework of the project performance](image)

2.2. Sustainability Impacts of the Key Indicators

Any type of construction may impact the sustainability of the environment. Since hydropower is one of the most efficient types of green energy, restoration work of a hydropower facility must be done such that its impacts on the environment should be minimized. The sustainable safety of construction, which includes construction and operation phases, is the basic function that engineers should pay attention to. Figure 6 shows the sustainability impacts of the key items.
2.3. Development of Solutions for Restoration Project-Related Problems

Restoration work may involve certain severe and dangerous conditions, which cause serious safety problems. Figure 5 shows the development of solutions for such problems.

Figure 7. Solutions for the problems faced in the Guguan hydroelectric power station restoration project

3. Problems Faced in the Restoration Project

3.1. Attack by Typhoons and Heavy Storms

The restoration project of the power station started in April 2002 and the station was engaged in commercial operation in late October 2008. During the execution of the project, typhoons and storms had repeatedly attacked the work site. Most of the construction facilities, access roads, and bridges were
damaged in these typhoons and storms, severely hindering the restoration work. Table 1 shows the typhoons and storms that occurred between 2004 and 2007.

Table 1. Typhoons and storms that occurred between 2004 and 2007

| Date         | Typhoon/Storm         | Major damage description                                      | Results                                         |
|--------------|-----------------------|---------------------------------------------------------------|------------------------------------------------|
| July 2, 2004 | Typhoon Mindulle      | 1. Raise of riverbed elevation up to 10 m                     | 1. Flooding of the powerhouse and tunnels       |
|              |                       | 2. Massive groundwater leakage                                | 2. Interruption of transportation               |
|              |                       | 3. Destruction of the access suspension bridge                |                                                |
| August 24, 2004 | Typhoon Aere          | 1. Destruction of access roads, construction platforms, bridges | 1. Interruption of transportation               |
| October 25, 2004 | Typhoon Nockten       | 2. Massive groundwater leakage                                | 2. Suspension of construction work             |
| December 4, 2004 | Typhoon Nanmadol   |                                                               |                                                |
| July 18, 2005 | Typhoon Haitang      |                                                               |                                                |
| August 5, 2005 | Typhoon Matsa        | Collapse of 35K and 38K of No. 8 highway                      | Total disruption of traffic of connection roads |
| September 1, 2005 | Typhoon Talim      | 1. Destruction of access roads, construction platforms, bridges | 1. Interruption of transportation               |
| October 2, 2005 | Typhoon Longwang    | 2. Massive groundwater leakage                                | 2. Suspension of construction work             |
| June 9, 2006 | Heavy storm           | 1. Destruction of access roads, construction platforms, and bridges | 1. Interruption of transportation               |
| June 8, 2007 | Heavy storm           |                                                               | 2. Suspension of construction work             |
| September 13, 2008 | Typhoon Sinlaku    | Massive groundwater leakage                                   | Suspension of construction work                |
| September 30, 2008 | Typhoon Jangmi    | Massive groundwater leakage                                   | Suspension of construction work                |

The restoration work was interrupted majorly by Typhoons Mindulle, Matsa, Sinlaku, and Jangmi, as illustrated in Table 1. In the following section, the major safety related construction work to resolve the problems faced during the restoration work is described. Figure 8 shows the site conditions after typhoon Mindulle.
3.2. Massive Groundwater Leakage
Another severe problem was the large volume of groundwater leakage from the external walls of the powerhouse and tunnels due to typhoons and heavy storms that occurred during the entire restoration work. A series of well-planned operation and inspection procedures were established for performing grouting work. Table 2 shows the volume of groundwater leakage between 2004 and 2008.

|                        | Largest leakage between 2004 and 2006 | Leakage after September 13, 2008 (Typhoon Sinlaku) | Leakage after September 30, 2008 (Typhoon Jangmi) |
|------------------------|--------------------------------------|---------------------------------------------------|---------------------------------------------------|
| Powerhouse             | 10 cmm                               | 31.1 cmm                                          | 21.9 cmm                                          |
| Access tunnel          | 41 cmm                               | 14 cmm                                            | 10.85 cmm                                         |
| Drainage tunnel 1      | —                                    | 36 cmm                                            | 33 cmm                                            |
| Drainage tunnel 2      | 10 cmm                               | 1.54 cmm                                          | 10.97 cmm                                         |
| Pilot tunnel           | 6 cmm                                | 1.36 cmm                                          | 1.18 cmm                                          |
| Total                  | 67 cmm                               | 84 cmm                                            | 77.9 cmm                                          |

3.3. Tailrace Tunnel Outlet Submerged under Riverbed and Access Tunnel Damaged
As shown in Figures 4 and 8, after the 921 earthquake and Typhoon Toraji, the tailrace tunnel outlet was totally submerged under the riverbed, completely loosening the drain of the tailrace, and the access tunnel was damaged severely. Figure 9 shows the flooded access tunnel.
4. Methods to Enhance the Sustainable Construction and Results

4.1 Method 1: Rebuild Construction Platforms and Facilities

For the restoration project, some construction platforms and facilities were built. The most important temporary structures for construction work include an access road to the existing switchyard, access bridges, a cofferdam for the tailrace outlet structure, a platform for the entrance of the powerhouse ventilation duct, and a platform for the entrance of the upper valve chamber ventilation duct. These structures were destroyed during strong typhoons. Table 3 describes the solutions for rebuilding these temporary facilities as a solution for safety in construction work.

Table 3. Solutions for rebuilding temporary construction facilities

| Platforms/facilities destroyed                              | Solution                                                                 | Photos |
|------------------------------------------------------------|--------------------------------------------------------------------------|--------|
| Access road to existing switchyard                        | Rebuilding of the access road by strengthening the road base             | Figure 10 |
|                                                            | 1. Building of a temporary steel bridge                                 |        |
| Access bridges                                             | 2. Setting of a temporary gondola during restoration of the highway     | Figure 11 |
| Cofferdam for the tailrace outlet structure                 | Redesigning and rebuilding of the cofferdam                              | Figure 12 |
| Platform for the entrance of the powerhouse ventilation duct| Rebuilding of the temporary platform with a strengthened steel frame    | Figure 13 |
| Platform for the entrance of the upper valve chamber ventilation duct | Rebuilding of the temporary platform with a strengthened retaining wall system | Figure 14 |
|                                                            | Building of the temporary bridge with strengthened supporting system     |        |
|                                                            | 1. Building of temporary steel bridge                                   |        |
| Steel bridge of No.8 highway 35K                           | 2. Temporary gondola were set during restoration of highway              | Figure 15 |
| Rock Shed of No.8 highway 38K                             |                                                                          |        |

Figure 10. Access road to existing switchyard: (a) the original access road (b) after typhoon Mindulle, (c) after rebuilding
Figure 11. Access bridge to the powerhouse: (a) original bridge, (b) after typhoon Mindulle, (c) the temporary steel bridge, (d) the temporary gondola

Figure 12. Cofferdam for tailrace outlet structure: (a) original cofferdam, (b) after typhoon Mindulle, (c) new rebuilt and strengthened cofferdam

Figure 13. Platform for the entrance of the powerhouse ventilation duct: (a) original platform, (b) after typhoon Mindulle, (c) new rebuilt and strengthened platform
4.2 Method 2: Grouting
Several different methods were discussed and selected to seal water leakage caused by strong typhoons and heavy storms that occurred during the restoration work. In this paper, the authors present the widely used sleeved pipe grouting method; its working procedure is shown in Figure 17.
**Figure 17.** Working procedure of the sleeved pipe grouting method Reference: New Asia Corp. grouting working plan 2004 (Figure representation by Tai-Yi Liu)

In this method, the grouting is divided into two stages and the mixture of grouting materials and grouting pressure are carefully designed to provide the best results of leakage sealing, as shown in Table 4.

**Table 4.** Mixture of grouting materials and grouting pressure for sleeved pipe grouting Reference: New Asia Corp. grouting working plan 2004 (Summarized by Tai-Yi Liu)

| Stage 1 | Materials       | Quantity | Pressure (5–40 kg/cm²) | Remark |
|---------|-----------------|----------|------------------------|--------|
|         | Cement          | 300 kg   |                        | CB mixed slurry |
|         | Bentonite       | 60 kg    |                        |        |
|         | Water           | 880 kg   |                        |        |
|         | Total           | 1,000 L  |                        |        |
|         | Cement          | 152 kg   |                        |        |
|         | Water           | 152 L    |                        |        |
|         | Subtotal        | 200 L    |                        |        |
| Stage 2 | Sodium silicate| 100 L    |                        | W/(C+F) = 1/(1+0.4)– 0.6/(1+0.4) |
|         | Water           | 100 L    |                        |        |
|         | Subtotal        | 200 L    |                        |        |
|         | Total           | 400 L    |                        |        |

The grouted curtain was created to minimize the volume of groundwater leakage. Figure 18 shows the improvement of groundwater leakage in the access and drainage tunnels before and after grouting. Figure 19 shows the grouting arrangement for the powerhouse area.
Figure 18. Improvement of groundwater leakage in access tunnel and drainage tunnel (a) before (b) after grouting Reference: New Asia Corp. grouting working plan 2004 (Figure representation by Tai-Yi Liu)

Figure 19. Grouting arrangement for the powerhouse area. Reference: Che-Yu Hwang (Figure representation by Tai-Yi Liu)
4.3 Method 3: Demolish and Rebuild the Inner Structures of Powerhouse

The power station was severely damaged during the 921 earthquake and Typhoon Toraji, and careful evaluation showed that the structures of this underground building were unsafe. For safe operation of the power station, engineers determined to demolish the inner structures including the walls and slabs and rebuild them by replacing hydraulic turbines and generators. Figure 20 shows the removal of the structures and turbines from inside the powerhouse. Figure 21 shows reinstallation of new turbines and generators. The rebuilt powerhouse with new generators is shown in Figure 22.

![Figure 20. Removal of structures and turbines inside powerhouse Reference: Che-Yu Hwang (Figure representation by Tai-Yi Liu)](image)

![Figure 21. Reinstallation of new turbines and generators Reference: Che-Yu Hwang (Figure representation by Tai-Yi Liu)](image)
4.4 Method 4: Rebuild the Tailrace Tunnel and Access Tunnel

The tailrace tunnel and access tunnel were severely damaged during the 921 earthquake and Typhoon Toraji as mentioned in Section 3.3. Engineers decided to extend these two tunnels to downstream of the Dajia River. The total lengths of the tailrace tunnel and access tunnel were 1,991 m and 2,098 m, respectively. Figure 23 shows the main structures that were rebuilt or newly constructed in the Guguan hydropower station restoration project.

Figure 22. Rebuilt powerhouse with new generators Reference: Che-Yu Hwang (Figure representation by Tai-Yi Liu)

Figure 23. Overall Guguan hydropower station restoration project: (a) the plan view (b) the pilot plan Reference: Che-Yu Hwang (Figure representation by Tai-Yi Liu)
5. Conclusion

In this paper, the authors focus on solutions for sustainable construction during and after restoration project. Other major sustainability issues are not discussed here. During the Guguan hydropower restoration project from 2004 to 2007, engineers faced severe problems such as occurrence of typhoons and storms, massive groundwater leakage, damage and destruction of tunnels and the powerhouse, and destruction of construction facilities and platforms, all of which resulted in unsafe conditions for the restoration work. To maintain safety of construction in the restoration project, engineers investigated and determined sustainable solutions. A well-planned grouting scheme resolved the groundwater leakage problem successfully. Rebuilding of the access tunnel and extension of the tailrace tunnel ensured safety for future operation of the power station. Rebuilding of all destroyed construction facilities and platforms also provided a safe environment for the restoration work. The authors therefore conclude that effective and sustainable construction has been maintained in the Guguan hydropower restoration project.

Acknowledgements

We would like to express our special thanks to the civil construction office of the Guguan site office of Taiwan Power Company, including the director, deputy directors, and engineers, for their instruction and supervision of the construction work by contractors for the Guguan hydropower restoration project. This greatly helped us in completing the study. Furthermore, their efforts to manage the construction safety ensured that no injury or accidents occurred during the restoration work as well as provided proper safety conditions for future operation of the Guguan hydropower station.

References

[1] World Bank. (1994). World development rep. 1994: Infrastructure for development, Oxford University Press, Oxford, UK, 1–12.
[2] World Bank. (2006). “Infrastructure at the crossroads: Lessons from 20 years of World Bank experience.” Washington, DC, 1–9, 65–80.
[3] Liyin Shen, M. ASCE, Yuzhe Wu, and Xiaoling Zhang, Ph.D. (2011). “Key Assessment Indicators for the Sustainability of Infrastructure Projects.” J. Constr. Eng. Manage., ASCE 137(6): 441-451
[4] Yun Zhong, Florence Yean Yng Ling, and Peng Wu (2016). “Using Multiple Attribute Value Technique for the Selection of Structural Frame Material to Achieve Sustainability and Constructability.” J. Constr. Eng. Manage., ASCE 143(2): 04016098
[5] Buede, D. M., and Maxwell, D. T. (1995). “Rank disagreement: A comparison of multi-criteria methodologies.” J. Multi-Criteria Decis. Anal., 4(1), 1–21.
[6] Yongtao Tan, Liyin Shen, Hong Yao (2011). “Sustainable construction practice and contractors’ competitiveness: A preliminary study”, Habitat International, 35 (2011) 225e230
[7] Peter Truitt (2009). “Potential for Reducing Greenhouse Gas Emissions in the Construction sector”, US EPA Archive Document, February 2009
[8] Mendler, F. S., and Odell, W. (2000). The HOK guidebook to sustainable design, Wiley, New York.
[9] Jincheol Lee; Tuncer B. Edil, Dist. M. ASCE; Craig H. Benson, F. ASCE; and James M. Tinjum, M. ASCE (2013). “Building Environmentally and Economically Sustainable Transportation Infrastructure: Green Highway Rating System.” J. Multi-Criteria Decis. Anal., 139(12): A4013006.
[10] Yuon-Hsien Hsiao, Research on the restoration project of Guguan hydropower station, Sino-Tech engineering consultant Inc., Journal No.108, 2010: 95~105 (in Chinese)
[11] Che-Yu Hwang, Final report for the Guguan hydropower station restoration project, Taipower, Presentation report (in Chinese)
[12] ASTM C1019-14, Standard Test Method for Sampling and Testing Grout, USA: American Society for Testing and Materials, 2014
[13] New Asia Construction and Development Corp., The grouting method working plan for Guguan hydropower restoration project, Taiwan, R.O.C., 2004 (in Chinese)
[14] New Asia Construction and Development Corp., The access tunnel working plan for Guguan hydropower restoration project, Taiwan, R.O.C., 2004 (in Chinese)
[15] New Asia Construction and Development Corp., The safety construction plan for Guguan hydropower restoration project, Taiwan, R.O.C., 2004 (in Chinese)