

Article

Analytical Framework for Understanding the Differences between Technical Standards Originating from Various Regions to Improve International Hydropower Project Delivery

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Abstract: The international hydropower construction market is continuously growing during the past decade. The existing literature points out that contractors are facing ongoing difficulties in achieving the objectives of developing international hydropower projects, which largely arise from the misunderstanding and poor use of international technical standards. However, there is a lack of a coherent framework to help systematically analyze the differences between technical standards originating from various regions. This study establishes an analytical framework that incorporates the essential factors of technical standards, namely philosophy of standards, logical structure, completeness of standards, calculation method, equipment and material requirements, test method, construction method, and application conditions of standards, and demonstrates their relationships from a holistic perspective. With support of the data collected from Chinese contractors, the results revealed the application status of various technical standards and their differences. Hierarchical cluster analysis demonstrates that unfamiliarity with the differences between domestic and international technical standards can cause multiple problems in international hydropower project delivery, concerning applying international standards, integrated project management, design, procurement, and construction, which have broad theoretical and practical implications. The outcomes of this study can not only help contractors improve their capabilities of applying international standards for achieving superior international hydropower project performance, but also facilitate mutual recognition of the standards from various regions, thereby maximizing the effectiveness of global resources such as expertise, technologies, methods, and products.

Keywords: technical standards; international hydropower projects; project delivery; analytical framework; design; procurement; construction



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1. Introduction

Technical standards are defined as documents that can be used to ensure that products, processes, services, and materials are fit for their purpose by providing characteristics, guidelines, or specifications [1], which should be established by consensus, and approved by recognized organizations [2]. Technical standards in the construction industry provide a set of guiding rules that assure the quality and safety of products and services involved in construction, standardize published documents such as data or product service information, ensure the compatibility of products, and decrease the economic losses due to product diversity [3].

Over the past decade, the international construction market is maintaining a continuous growth trend, with the annual contract value of the top 250 international contractors increasing from \$383.8 billion in 2009 to \$625.8 billion in 2019 [4,5]. This demonstrates that international project delivery is playing a more and more important role in the global

economy [6]. Nevertheless, contractors are facing a greater challenge in delivering international projects than domestic projects because they need to work in a different institutional environment [7], in which the difference between domestic and international technical standards is a key issue that influences project performance [8–11].

As an instrumental component of industrial technological infrastructure [12], technical standard is recognized as one of the critical parts of knowledge for contractors to learn in the international construction industry [8,10,13,14]. A lack of knowledge of the differences between technical standards can increase misunderstandings in international project implementation processes, resulting in delays and cost overruns [15]. Zhang (2018) confirmed that the problems related to applying international technical standards on design and construction are main barriers for contractors to promote their performance in projects abroad [11]. Although the Standardization Administration of China (SAC) is a member of ISO, many researchers have pointed out the importance of learning the differences of standards originated from various countries [10,15–18], and there is still a lack of coherent framework to help systematically analyze the differences between technical standards originating from various regions. This has led to the previous comparative studies between different technical standards to largely remain at the prescriptive level, and relevant empirical evidence regarding the application of international standards have been piecemeal. Therefore, the aim of this study is to establish an analytical framework that incorporates the essential factors of technical standards, which helps understanding the differences between domestic and international technical standards together with their impacts on international hydropower project delivery from a holistic perspective.

This study has made a significant contribution to the body of knowledge both theoretically and practically. Firstly, this research has established an analytical framework that incorporates eight essential factors of technical standards, and demonstrates their relationships in a systematic way, providing a theoretical base for understanding the differences between standards originating from various countries/regions from a holistic view. Secondly, this study has quantitatively measured the differences between Chinese and international technical standards, and revealed how these differences affect the delivery of international hydropower projects, which provide a sound basis for contractors dealing with problems related to unfamiliarity with the differences of standards. Thirdly, the findings of this study suggest broad practical strategies, such as comparative study between standards, case studies, training, and cooperation among participants; choosing suitable suppliers worldwide; and coordinating the standards of design, procurement, and construction. These strategies can not only help contractors improve their capabilities of applying international standards for achieving superior international hydropower project performance, but also facilitate mutual recognition of the standards from various countries/regions, thereby maximizing the effectiveness of global resources such as expertise, technologies, methods, and products.

2. Analytical Framework for Understanding the Differences between Domestic and International Technical Standards

Many researchers have pointed out that technical standards from various regions can be substantially different [13,19–26]. Lei et al. (2016) confirmed that the Chinese contractors perceived a significant difference between international standards and Chinese standards, and they faced greater challenges in implementing international standards in international projects [10]. The misunderstanding of requirements in technical standards is one of the important causes of poor profitability in overseas construction projects [23]. Insufficient understanding of the differences between domestic and international technical standards can lead to vague definitions in contracts, which is a main cause of disputes in international engineering–procurement–construction (EPC) projects [9]. “Unfamiliarity with the differences in project standards at home and abroad” ranked first among design-related problems for contractors’ implementation of international hydropower projects [11]. Even though in some international hydropower projects, the contractors were allowed to

apply Chinese standards to designs due to the project-located region lacking relevant design standards, the contractors still faced a significant challenge, which arose from the domestic design standards not being compatible with international construction and procurement standards, leading to unnecessary rework and cost growth of the construction [14].

The existing studies suggest that understanding the differences between standards originating from various regions covers broad themes, which can be refined as the following essential factors, as shown in Figure 1 [8,11,14,17,18,24–26].

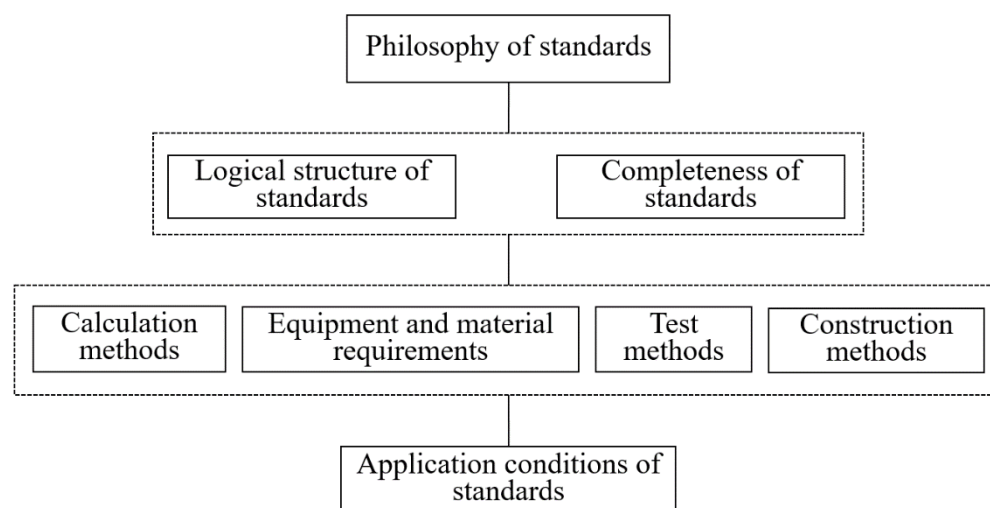


Figure 1. Analytical framework for technical standards.

Different philosophies of standards may have their respective emphasis on achieving the objectives regarding safety, economy, environmental protection, and applicability. The underlying principles in a philosophy of standards act as directives to develop standards in different countries, thereby influencing logical structure and completeness of standards. Following the established logical structure (e.g., engineering projects adhere to the logic of design, procurement, and construction), the calculation methods, equipment requirements, construction methods, and test methods for projects can be standardized and developed. As the projects located in various countries have their respective environmental and technical features, the application conditions of standards should be specified accordingly. The key factors in the analytical framework for understanding the differences between domestic and international technical standards are characterized below.

(1) Philosophy of standards. A philosophy of standards reflects the ways of balancing the safety, economic, environmentally-friendly, and applicability principles underlying the standards. Roles of the principles embedded in the philosophy of standards can be different in various countries, and this is attributed to the fact that the technical and economic factors in a given area can largely affect formation of the standards [8]. One standard in a country may have stricter requirements on environmental issues, whereas the corresponding standard in another country may consider economic principles more [27].

(2) Logical structure of standards. The logical structure between a series of standards in one standard system and the logical structure within an individual standard can vary from country to country. The cause of the logical structure difference can be attributed to legal systems, and some legal systems are based very heavily on cases, whereas others are not, which causes not only the way standards are structured, but also the way they are documented, to be very different across countries [8]. The different industrial conventions can also cause logical structure differences of standards between countries, and unfamiliarity with the international conventions may result in difficulties when applying international technical standards in international project delivery [10]. For example, failing to understand the logical structure differences of standards can lead to unclear specification

of contracts regarding the use of standards, and this can create an increase of legal risks in international project implementation [28].

(3) Completeness of standards. A technical standard usually specifies one or a class of technical requirements, which can usually cover the practical use in a certain area [25]. However, the standards of a country can become incomplete under some circumstances. When new technologies are innovated, existing standards would become incomplete, which can be attributed to the fact that standardization usually plays an important role in synchronizing the technical innovations into a systemic innovation [29]. With the development of societies, extant standards may also become incomplete to satisfy the advancing requirements of social management, and this is reflected in the continuous updating of standards on safety and environment protection. Inadequate consideration when preparing standards could account for the incompleteness of the standards. For instance, compared with IWS, ISO, BS, and EN standards, the Chinese standard (JB/T 3223-2017 Welding Consumables Quality Management Producers) has only specified the upper limit of humidity for storing welding material, but ignored the factor of temperature, which may lead to quality problems when processing welding work in high-humidity environments in summer [30].

(4) Calculation methods of standards. The calculation methods used in the technical standards can be different across countries. For example, there are differences between the approaches in calculating the influences of individual parameters among eight major international standards on wind loads [31]. There also exists substantial differences regarding the calculation methods of axial and bending stresses among American, European, and Korean wind load standards [18]. For the convenience of engineers in design, Chinese standards sometimes adopt empirical formulas derived from past project experience, whereas the corresponding international standards may apply different theoretical calculation methods [10]. When such Chinese standards are applied in international projects, the outcomes of calculation need to be validated by using the corresponding international standards to obtain approval from consultant engineers [11].

(5) Equipment and material requirements of standards. The physical properties of material and functional requirements of equipment may vary from country to country. For instance, the ways of grading on steel bars in standards from various countries are different with respective requirements of yield strength [24]. These differences on equipment and material requirements force domestic suppliers to redesign their products in order to satisfy the requirements of the adopted international standards, which increases the cost of procurement [32]. Sometimes, domestic suppliers may be excluded from the international market because they are unable to meet the requirements of international standards within the scheduled procurement time [33]. Understanding the differences between international and domestic technical standards regarding equipment and material requirements is critical for the new entrants to control procurement costs in delivering international projects [34].

(6) Test method of standards. Different standards may specify different test methods [26]. Take the strength test of concrete as an example: the American standard (ASTM C39/C39M-2018) and the corresponding Chinese standard specify different shapes of the specimen, and require different curing ages of the specimen [35]. Although the conversion relationship among different test methods can be established by calculations and experiments, contractors' unfamiliarity with the differences of test methods can result in an inappropriate choice of standards, and can then influence the testing efficiency in international project delivery [10].

(7) Construction method of standards. Standards derived from various countries may specify different construction methods. Unfamiliarity with these differences between domestic and international standards can result in improper preparation for construction, e.g., the procured plants that fit domestic construction methods may not match the requirements of international standards. This can lead to construction rework, delay, and increased costs in international project delivery [14].

(8) Application conditions of standards. Application conditions of standards can be different, and this can be attributed to both environmental and technical factors. The technical standards, such as design codes and construction specifications, can vary across countries in order to satisfy the unique local environmental conditions [17]. For instance, due to the different climate, concrete has a larger thermal shrinkage in Hong Kong than in the U.K.; therefore, the Hong Kong standard has specified a higher value for shrinkage of concrete than the corresponding British standard [8].

To understand the extent to which the impacts of unfamiliarity with differences between domestic and international technical standards have on international hydropower project delivery, the factors in the analytical framework (see Figure 1) need to be systematically investigated by a survey in the industry. The relevant empirical questions are as below:

- What is the frequency of using various technical standards in international hydropower projects?
- What are the differences between domestic and international technical standards regarding the factors of philosophy of standards, logical structure, completeness, equipment and material requirements, calculation methods, construction methods, test methods, and application conditions of standards?
- What are the impacts of unfamiliarity with the differences between domestic and international technical standards on delivering international hydropower projects?

3. Research Methodology

3.1. Reason for Choosing Chinese Contractors

Over the past decade, Chinese contractors are playing a more and more important role in the international construction industry, with more than 20% annual growth rate of contract amounts [6], with 74 Chinese contractors listed on the ENR's (Engineering News-records) 2020 top 250 international contractors [4]. Chinese companies achieved an international contract value of US\$120.05 billion in 2019, accounting for 25.4% of the total international contract value of the 250 listed companies, with an increase of 1% comparing with the previous year. Therefore, data collected from Chinese contractors in this study are representative for analyzing the differences between Chinese and international standards in the international construction industry.

3.2. Data Collection

This study adopted a triangulated approach, which can facilitate a deepened analysis for a research topic [36] by collecting both quantitative and qualitative data using the mixed methods of a questionnaire survey, interviews, and case studies.

The quantitative data was collected through a questionnaire survey designed on the basis of a literature review and the analytical framework established before (See Supplementary Materials). The questionnaire aims to investigate Chinese contractors' perceptions on how technical standards between China and abroad are different, and how a lack of knowledge of these differences affects the delivery of an international hydropower project. The respondents were requested to answer the questions according to their experience learned from international hydropower projects with which they were engaged. The questionnaire consists of four sections: (1) background of the respondent under investigation, and the project that he/she participated in; (2) frequency of using different technical standards; (3) the differences between Chinese and international technical standards; and (4) technical standard difference-related problems in project implementation. The respondents were requested to answer the questions according to their experience learned from international hydropower projects with which they were engaged. They were asked to answer the questions using a 5-point Likert scale in Sections 3 and 4 of the questionnaire.

Questionnaires were sent to 22 Chinese construction companies, which all had over 10 years' experience in overseas projects, and some of them had successfully constructed many internationally renowned projects. Former researchers had pointed out that ques-

tionnaire surveys via mail or e-mail frequently lead to a low response rate or a casual response [37]. In order to obtain more credible survey results, the questionnaires were sent and collected during field trips to the headquarters of the investigated Chinese contractors, as well as the meeting site of their project managers. As a result, all sent 362 questionnaires, distributed to the 22 construction companies according to their influences in the international market, were collected, and 294 of them were used for analysis, excluding 68 invalid ones with incomplete information. Each of the questionnaires was fulfilled according to the respondent's experience accumulated from an individual international hydropower project (each project has several samples). The distribution of these projects is shown in Figure 2, and the investigated projects were mainly scattered in Africa, the Middle East, Asia, and America (see Table 1), in which various standards were frequently adopted. Hence, the survey results obtained from these countries can well-facilitate this study on the differences between Chinese and international standards. The respondents have 8.8 years (on average) of abroad working experience.

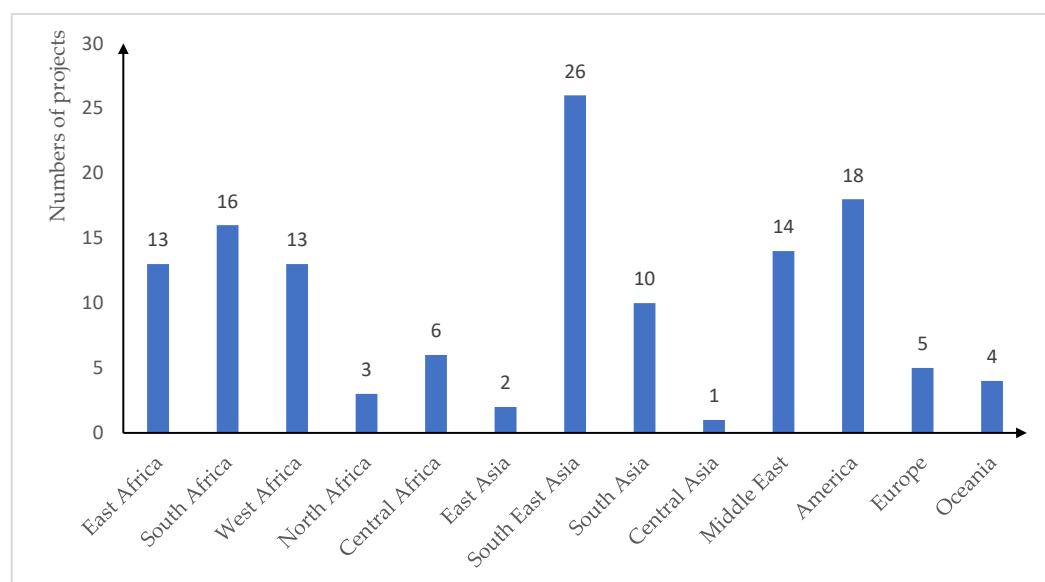


Figure 2. The distribution of projects in the questionnaire survey.

Table 1. The numbers of projects in the questionnaire survey.

Regions	Numbers of Projects Located in Different Countries/Regions
East Africa	4 (Uganda), 3 (Ethiopia), 2 (Sudan), 1 (Kenya), 1 (Rwanda), 1 (Tanzania), 1 (Djibouti)
South Africa	6 (Angola), 4 (Zambia), 2 (Mozambique), 2 (Zimbabwe), 1 (Namibia), 1 (Senegal)
West Africa	3 (Guinea), 2 (Nigeria), 2 (Niger), 2 (Cote d'Ivoire), 1 (Benin), 1 (Gambia), 1 (Ghana), 1 (Liberia)
North Africa	3 (Algeria)
Central Africa	2 (Equatorial Guinea), 2 (Cameroon), 1 (Republic of the Congo), 1 (The Democratic Republic of the Congo)
East Asia	1 (South Korea), 1 (Hong Kong China)
South East Asia	6 (Malaysia), 5 (Indonesia), 4 (Laos), 3 (Myanmar), 3 (Vietnam), 2 (Cambodia), 1 (Thailand), 1 (Singapore), 1 (Timor-Leste)
South Asia	4 (Pakistan), 3 (Nepal), 2 (Sri Lanka), 1 (India)
Central Asia	1 (Tajikistan)
Middle East	4 (Qatar), 3 (Israel), 3 (Saudi Arabia), 2 (Kuwait), 2 (The United Arab Emirates)
America	6 (Venezuela), 4 (Ecuador), 1 (Colombia), 1 (Costa Rica), 1 (Cuba), 2 (Trinidad and Tobago), 2 (Bolivia), 1 (Honduras)
Europe	2 (Belarus), 1 (Serbia), 1 (Russia), 1 (Macedonia)
Oceania	2 (Fiji), 1 (Papua New Guinea), 1 (Vanuatu)
Total	131

Face-to-face semi-structured interviews with 49 managers from these Chinese contractors were conducted right after the questionnaire survey. The selected interviewees all had rich experience in international construction projects, and held senior positions in their respective companies, e.g., CEOs/general managers, project managers, chief or deputy chief engineers, and directors of departments. The interviewees were asked to share their perceptions on standards and the problems related to standards during the implementation of overseas projects concerned with their management scopes, respectively, e.g., design management, construction management, procurement management, and occupational health and environmental protection management.

Ten international project cases (see Table 2) were further extracted from project documents, and collected by the authors for case studies in order to confirm the findings from survey results, and further explain the differences between Chinese and international standards, and their impacts on international hydropower project delivery.

Table 2. Profiles of international hydropower project cases collected in this study.

Project Name	Contract Value (Million Dollars)	Mainly Applied Standards
Pakistan Gomal Zam Hydropower Project	87	ASTM, ACI, IEC, and other equivalent standard accepted by the client
Angola N'zeto-Soyo Highway Project	605	AASHTO, ACI, ASTM, BS, DIN, ISO, NF, and IBC
Qatar Luce CP1 Project	1430	BS, ISO, ASTM, and Qatar standards
Fiji Nadarivatu Renewable Power Project	124	AS/NZS, IEC, BS, ISO, ASCE, ASTM, ACI, and Fiji standards (FJS)
Mali Felu Hydropower Project	170	EN, USACE, ACI, IEC, ASTM, ISO, DIN
Zambia Itaiz Hydropower Project	138	BS, EN, ISO, USACE, USBR, ASTM, ACI, ASCE, and IEC
Ethiopia Tekeze Hydropower Project	224	ISO, IEC, ASTM, BS, and Chinese standards
Ghana Buvi Hydropower Project	596	USACE, Chinese standards, ASTM, BS, and ACI
Malaysia Bakun Hydropower Project	813	ASTM, Chinese standards, USBR, USACE, ACI, and BS
Ecuador Coca Codo Sinclair Hydropower Project	1980	ASTM, ACI, USBR, AASHTO, Chinese standards, and Ecuador standards

3.3. Data Analysis

With the help of the software Statistical Package for Social Science (IBM SPSS Statistics 24.0), ranking analysis, hierarchical cluster analysis, and a Cronbach's alpha reliability test were applied in this research. Rank analysis was used to reveal the current application status of different technical standards applied in international hydropower projects, and to quantitatively measure the differences between Chinese and international technical standards, and the impacts of unfamiliarity with these differences on international hydropower project delivery. Cronbach's alpha reliability testing was conducted in order to validate the internal consistency, with the value of Cronbach's alpha between 0.6 and 0.7 considered as acceptable, and larger than 0.7 regarded as good [38]. Hierarchical cluster analysis is a useful tool to reveal the relationships among variables, and identify relatively homogeneous groups based on selected characteristics [39]. Hierarchical cluster analysis was performed to exhibit the relationships among problems related to unfamiliarity with differences between Chinese and international standards for classification. Afterwards, the quantitative results were further analyzed and discussed by referring to the interviews and case studies. The adopted triangulated approach helps provide an in-depth understanding of Chinese contractors' practices on standards in international hydropower projects.

4. Results and Analysis

4.1. Frequency of Using Different Technical Standards

Eighteen kinds of technical standards that have important influence worldwide were selected as the research objects. Respondents were requested to identify whether or not these selected technical standards were used in the projects that they were engaged with. The using frequency of standards from different organizations was then calculated, and is shown in Table 3.

Table 3. Using frequency of different technical standards in international hydropower projects.

Technical Standards	Using Frequency (Represented by Percentage)	Rank
American Society for Testing and Materials (ASTM)	52%	1
International Organization for Standardization (ISO)	47%	2
Chinese Standards	46%	3
American Concrete Institute (ACI)	32%	4
European Norm (EN)	31%	5
British Standard (BS)	29%	6
International Electrotechnical Commission (IEC)	20%	7
The American Society of Mechanical Engineers (ASME)	19%	8
Institute of Electrical and Electronics Engineers (IEEE)	17%	9
German Institute for Standardization (DIN)	15%	10
The American Society of Civil Engineers (ASCE)	14%	11
French Standards Association (NF)	13%	12
American Association of State Highway and Transportation Officials (AASHTO)	13%	13
United States Army Corps of Engineers (USACE)	12%	14
United States Bureau of Reclamation (USBR)	8%	15
International Telecommunication Union (ITU)	6%	16
Australian Standards/New Zealand Standards (AS/NZS)	4%	17
Indian standards	2%	18

Since the data were collected through a survey of 17 representative Chinese construction companies, the result can well-reflect the frequency of using different kinds of technical standards in international hydropower projects delivered by Chinese contractors. As shown in Table 3, American standards (ASTM, ACI, ASME, IEEE, ASCE, AASHTO, USACE, and USBR), European Standards (EN, BS, DIN, and NF), ISO standards, and Chinese standards are most frequently used in the international hydropower projects delivered by Chinese contractors. Specifically, the frequencies of using ASTM, ISO, Chinese standards, ACI, and EN rank top five, with 52%, 47%, 46%, 32%, and 31%, respectively.

4.2. The Differences between Chinese and International Technical Standards

Eight aspects were selected to evaluate the differences between Chinese and international technical standards, including philosophy of standards, logical structure of standards, completeness of standards, equipment and material requirements, calculation methods, construction methods, test methods, and application conditions of standards. The respondents were asked to rate the differences on these aspects using a 5-point Likert scale, with 1 = no difference, 2 = small difference, 3 = neither big nor small difference, 4 = big difference, and 5 = very big differences. Results are shown in Figure 3.

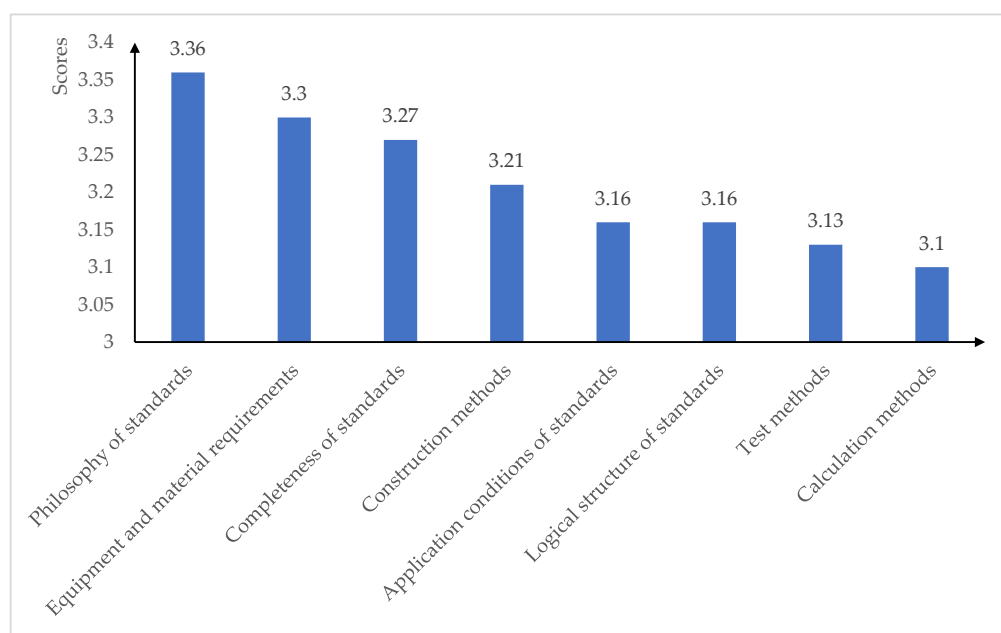


Figure 3. The differences between Chinese and international technical standards.

The results in Figure 3 show that the scores of all the aspects are above 3.0, indicating that there are differences between Chinese and international technical standards in all aspects.

“Philosophy of standards” is ranked first, with a score of 3.36, showing that there is an apparent difference between Chinese and international standards regarding safety, economic, environmentally-friendly, and applicability principles. For example, some interviewed managers indicated that applying Chinese standards on the development of hydropower projects may result in much higher construction costs than using international standards, demonstrating the difference in the economic principles of the philosophies of standards. Regarding applicability principles, Chinese standards often provide specific methods so that engineers can use the standards as manuals in design and construction processes, facilitating the efficiency of using the standards. The interviewed managers pointed out that American and European standards stress more on theories, and require engineers to give appropriate solutions by their own judgement according to the site conditions, keeping the flexibility of the standards in their application. For example, during the roll-cast concrete pouring construction of a hydropower project in Pakistan, to improve the efficiency of the project delivery, the contractor used Chinese standards to guide the design and construction, and used international standards for inspection and handover.

“Equipment and material requirements” is ranked second, with a score of 3.30, indicating that the functional requirements of the equipment, and the physical properties of the material specified in different technical standards, could be quite different. Take steel as an example: an interviewed manager mentioned that there are differences in brittleness requirements of steel between Chinese and international technical standards. In a road project in Angola, the project contract specified to use G60 steel bars defined by ASTM standards. Considering procurement convenience, the Chinese contractor requested to use HRB400 steel bars, defined by Chinese standards, instead of G60 steel bars. However, it was found that the yield strength of G60 steel bars is 420 MPa, whereas that of HRB400 is 400 MPa. The G60 steel bar has higher strength, but is more brittle compared with the HRB400 steel bar, which can cause a higher possibility of breakage when bent under relatively low temperature. Considering these, the request of replacing G60 steel bars by HRB400 steel bars was not approved by the consultant. As a result, the contractor was unable to take advantage of Chinese suppliers that could provide more cost-effective

steel, demonstrating the need for understanding the differences between Chinese and international standards in early stages of the contracting process.

“Completeness of standards” is ranked third, with a score of 3.27, which shows a non-negligible difference between Chinese and international standards. Understanding the differences between Chinese and international standard systems can help to complement the completeness of standards with each other. For example, when the need to have a standard covering occupational health and safety was realized, Chinese standards added GB/T 28001-2011 (Occupational Health and Safety Management Systems-Requirements), which was derived from a British standard, BS OHSAS 18001-2007 (Occupational Health and Safety Assessment Series). Similarly, ISO 45001-2018 (Occupational Health and Safety Management Systems-Requirements with Guidance for Use) was also derived from BS OHSAS 18001 [40–42]. There are also completeness differences between one Chinese standard and the corresponding international standard. Take technical standards for concrete durability design as an example: DIN EN 1992-4-2019 (Design of Concrete Structures-Part 4: Design of Fastenings for Use in Concrete) and DIN EN 206-2017 (Concrete-Specification, Performance, Production, and Conformity) mainly focus on the classification of environmental conditions, equipment, and material requirements and design working life, whereas the Chinese standard GB/T 50476-2019 (Standard for Design of Concrete Structure Durability) has made additional provisions on protective structures and measures [43], which is convenient for concrete structure design considering durability.

“Construction methods” is ranked forth, with a score of 3.21, showing that there are also differences in construction methods between Chinese and international technical standards. For example, the construction methods of treating steel bars are different between Chinese and BS standards: British standards stipulate that steel bars are not allowed to be welded, and require mechanical connection methods, whereas in Chinese standards, welding is more frequently used than mechanical connection methods for the purpose of saving steel. In a municipal project in Qatar, it is specified by Qatar standards that the contractor should find out all of the existing underground infrastructure, mark the location on the drawings, and have them approved before construction, whereas Chinese standards make no specific requirements. In preparing construction plans, the influences of the difference between Chinese and international construction methods should be carefully considered.

“Application conditions of standards” is ranked fifth, with a score of 3.16, which indicates that there are differences in application conditions between Chinese and international standards. For example, a hydropower project delivered by a Chinese contractor in Fiji used AS/NZS standards. Due to the strong typhoons that may occur in the Oceania region, the AS/NZS standard stipulates that the power transmission and transformation infrastructure should resist a wind load much higher than what is specified by the Chinese standard. Another example is a project in Saudi Arabia delivered by a Chinese contractor. Regarding the design of an air conditioning system, the design outdoor temperature is 38 degrees Celsius according to Chinese standards; however, this design temperature cannot match the local temperature conditions, which can reach 46 degrees Celsius. These demonstrate that the different application conditions between Chinese and international standards have to be considered.

“Logical structure of standards” is ranked sixth, with a score of 3.16, showing that there are differences in logical structure between Chinese and international standards. Take concrete as an example: DIN EN 206-2017 (Concrete-Specification, Performance, Production, and Conformity) clearly describes the logical structure among standards for design and execution, standards for constituents, and test standards [44]. Comparatively, American and Chinese concrete standards lack such a generic logical structure. American and Chinese concrete standards are normally made by American associations (ASTM, ACI, AASHTO, etc.) and Chinese industrial sectors (building, transportation, energy, etc.), respectively. The standardization work of different associations and industrial sectors develop at different

paces, and this may result in incompatibility between different standards, which should be paid attention to when delivering international hydropower projects.

“Test methods” is ranked seventh, with a score of 3.13, showing differences regarding test methods between Chinese and international standards. Take compressive strength test of concrete as an example: ASTM C39/C39M-2018 (Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens) specifies using $\varnothing 150 \times 300$ mm cylindrical concrete specimens, whereas the Chinese standard GB/T 50081-2019 (Standard for Test Methods of Concrete Physical and Mechanical Properties) usually specifies using $150 \times 150 \times 150$ mm cube concrete specimens [35,45]. There are also differences in concrete testing requirements between Chinese and European standards. For instance, in Mali, a hydropower project delivered by a Chinese contractor used EN standards. The EN standard specified that the concrete specimens should be kept curing for 90 days before testing, which is much longer than 28 days specified by the corresponding Chinese standard. To improve the efficiency of testing, the contractor established the strength conversion relationship between the 90-day-age concrete and the 28-day-age concrete through a 3-month field test. The results were approved by the consultant, and then the contractor conducted the test according to the requirements of the Chinese standard, which shortened the test time significantly.

“Calculation methods” is ranked eighth, with a score of 3.10, indicating that the differences between Chinese and American standards regarding calculation method should not be ignored. For example, in a project delivered by a Chinese contractor in Zambia, ASTM standards were used for designing the structure. ASTM standards use a strength reduction coefficient and a load coefficient to calculate the bearing capacity of the structure under three states: normal, abnormal, and extreme load conditions, whereas Chinese standards use the ultimate limit state method, using five partial factors for calculating the bearing capacity of the structure. The different theories applied between Chinese and international standards should be paid attention to when delivering international hydropower projects.

4.3. Problems Related to Unfamiliarity with Differences between Chinese and International Standards in International Hydropower Project Delivery

Due to the unfamiliarity with the differences between Chinese and international standards, Chinese contractors may get involved in different kinds of problems when delivering international hydropower projects. Twenty problems related to unfamiliarity with the differences between Chinese and international standards in international hydropower project delivery were identified, and the respondents were asked to rate the occurrence frequency of the problems by using a Likert scale, with 1 = never happened, 2 = seldom happened, 3 = sometimes happened, 4 = often happened, and 5 = always happened. The hierarchical cluster analysis technique was used for classification, with the results presented in Figures 4 and 5.

The reliability test shows that the value of Cronbach's α for all of the five sorts of problems are larger than 0.85, indicating a good consistency for all of the five classifications, demonstrating the reliability of the results. The 20 problems obtained ratings ranging from 2.64 to 3.46 (see Figure 5), indicating that the problems caused by unfamiliarity with the differences of standards should not be ignored. These problems can be classified into five groups (see Figures 4 and 5):

(1) Problems of applying international standards related to unfamiliarity with differences of standards

The average score of problems with applying international standards is 3.11, ranking first among all the groups, and this indicates that the most significant impact of unfamiliarity with the differences of standards is that the Chinese contractors could not well-apply international standards in international hydropower projects. This issue is closely related to other groups (see Figure 4), and can cause problems of design, procurement, construction, and integrated management in international hydropower project delivery (see Figure 5).

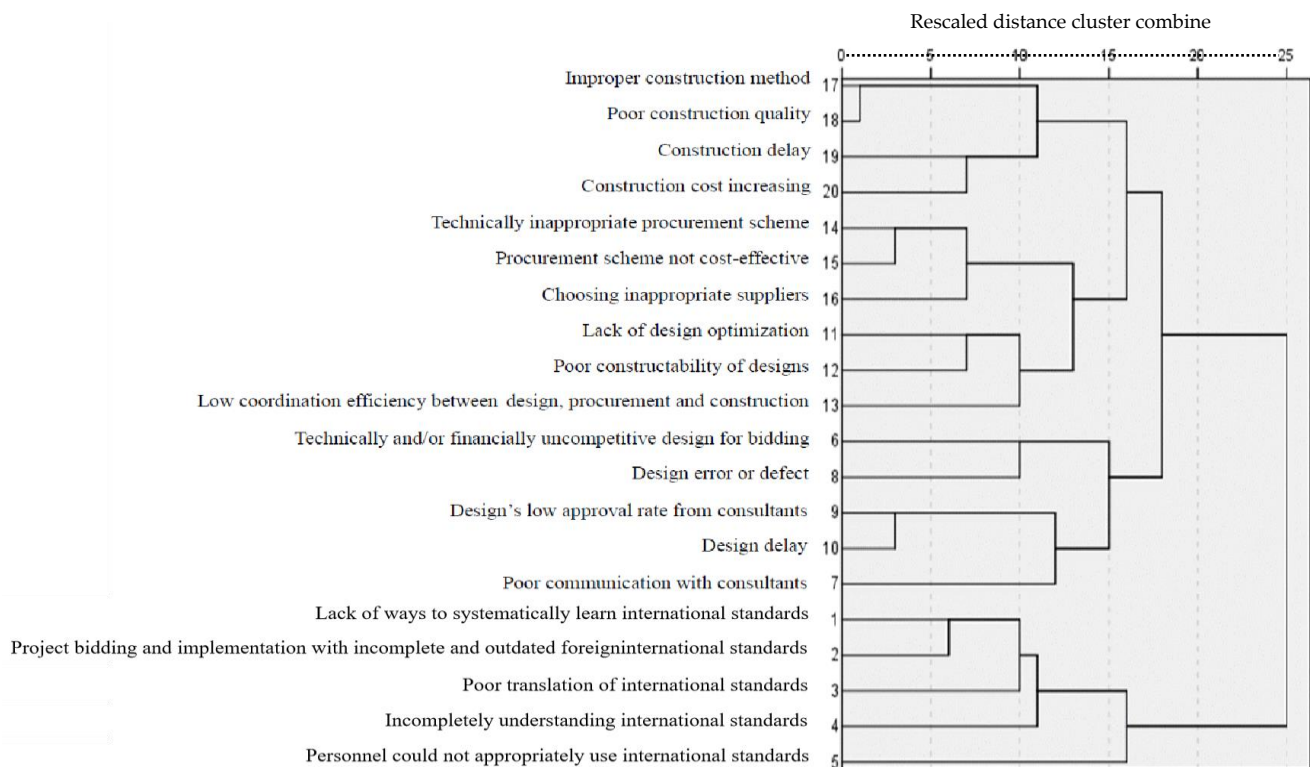


Figure 4. Hierarchical cluster analysis for problems related to unfamiliarity with differences between Chinese and international standards in international hydropower project delivery.

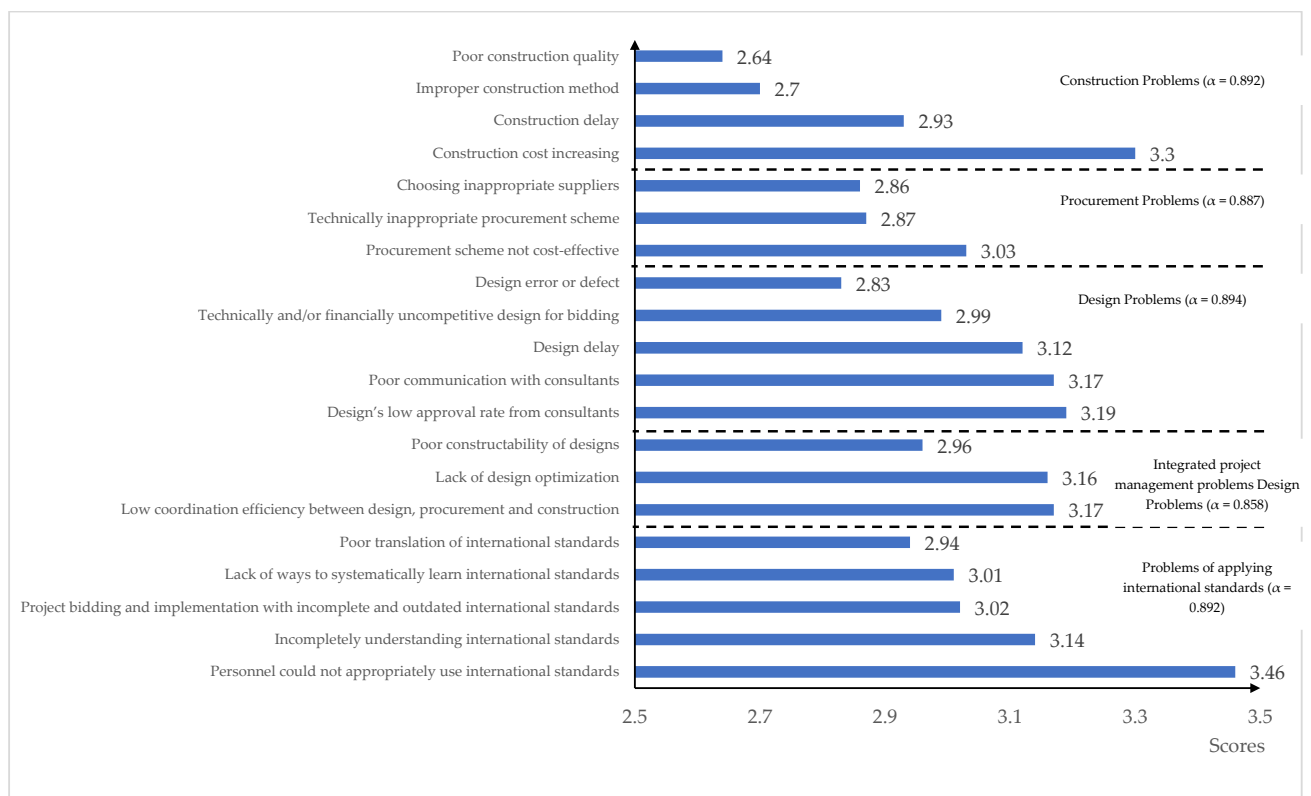


Figure 5. Problems related to unfamiliarity with differences between Chinese and international standards in international hydropower project delivery.

“Personnel could not appropriately use international standards” obtains the highest rating among all (see Figure 5), showing that the key challenge to the management and technical staff of Chinese contractors is the improper application of international standards in international hydropower projects. As shown in Figure 4, the problem of using international standards is closely related to “lack of ways to systematically learn international standards”, “project bidding and implementation with incomplete and outdated international standards”, “poor translation of international standards”, and “incompletely understanding international standards”. The interviewed managers confirmed that their experience in using international standards is piecemeal and project-oriented, and, although having a strong intention to deepen the understanding of international standards, they lacked ways to obtain knowledge of relevant standards in a systematical manner. These demonstrate that, to improve the capability of using international standards, Chinese contractors should manage to establish a mechanism to permit their personnel access to learning the differences between Chinese and international standards by ways such as training on using standards, and sharing experience and lessons in different international hydropower project cases.

(2) Integrated project management problems related to unfamiliarity with differences of standards

The average score of integrated project management problems is 3.10 (see Figure 5), showing that unfamiliarity with the differences of standards could cause problems from a holistic management perspective. Notably, “low coordination efficiency between design, procurement and construction” is ranked fourth among all, and this shows that unfamiliarity of the differences between Chinese and international standards is a key barrier for coordinating design, equipment procurement, and construction activities. A lack of knowledge about the differences in equipment and material requirements, calculation methods, construction methods, and test methods can significantly affect the integrated management between design, procurement, and construction processes. For example, in the project in Fiji, the first version of the contractor’s Basic Design Report was not approved by the consultant because it lacked detailed parameters of the equipment, which was attributed to the contractor’s unfamiliarity with the equipment requirements of international standards. In dealing with this, the Chinese contractor inputted a lot of additional resources to coordinate with suppliers worldwide, thereby satisfying the consultant by incorporating the appropriate equipment parameters into the Basic Design Report.

“Lack of design optimization” and “poor constructability of designs” are also important problems arising from unfamiliarity of the differences between standards in terms of calculation methods and construction methods (see Figure 5). For example, in the Tekeze hydropower project in Africa, the contractor is a Chinese construction company, and the consulting company is from the USA. The contractor needed to complete the detailed design on the basis of the conceptual design given by the consulting company. However, due to the contractor’s unfamiliarity with the US standards, there were a lot of problems related to poor constructability, and even errors on the detailed designs in the early stage of project delivery.

(3) Design problems related to unfamiliarity with differences of standards

The average score of design problems is 3.06 (see Figure 5), indicating that many design problems could arise from unfamiliarity with the differences between Chinese and international standards. It is found that “design’s low approval rate from engineers” and “poor communication with engineers” are ranked third and fifth, respectively, among all. An interviewed manager pointed out that sometimes there are obvious different understandings of standards between Chinese contractors and the international consultant engineers, which can lead to communication barriers between them, and cause “design’s low approval rate from engineers”. As a result, designers had to spend more time on the revision of design products, leading to “design delay”. For example, in a project in Ghana, the consultant engineers were hired from France, who specified the project to adopt USACE standards, whereas the Chinese designer was used to applying Chinese

standards in delivering Chinese projects. Due to the unfamiliarity of the differences between the Chinese and the USACE standards regarding application conditions and calculation methods, the submitted design documents were frequently sent back for revising the “design error or defect”, and even some drawings had to be revised five times.

“Technically and/or financially uncompetitive design for bidding” is also an important issue caused by the unfamiliarity of differences between Chinese and international standards (see Figure 5). During the bidding stage, many clients of international hydropower projects only provide conceptual designs that define clients’ needs and functional requirements without any detailed designs, leaving high uncertainties for bidding. The Chinese designers’ unfamiliarity with the differences of standards, e.g., philosophy of standards, may lead to inappropriately using safety, economic, environmentally-friendly, and applicability principles during the design process, thereby resulting in an uncompetitive design for bidding.

(4) Procurement problems related to unfamiliarity with differences of standards

“Procurement scheme not cost-effective” obtains the highest rating among procurement problems (see Figure 5), and this suggests that an insufficient understanding of differences between the Chinese and international standards can affect the value for money of the procured equipment and materials in international hydropower projects. An interviewed expert pointed out that Chinese contractors tend to purchase equipment and materials from Chinese suppliers in order to cut procurement cost, since they have built long-term partnering relationships. However, due to unfamiliarity with the differences of standards, the contractor could not clearly explain the requirements and specifications to Chinese suppliers, who are used to following Chinese standards, resulting in the procured equipment and materials possibly not meeting the requirements of international standards. This could affect the preparation of the procurement scheme, as some Chinese suppliers that can provide more cost-effective products may be excluded. For example, in a project in Fiji that adopted AS/NZS standards, the contractor prepared a procurement scheme according to the Chinese standards at the bidding stage. However, at the implementation stage, it was found that the requirements of AS/NZS standards were different from those of Chinese standards, and, as a result, the contractor had to change the procurement scheme, and purchase the equipment from an abroad supplier whose price was much higher than that of Chinese suppliers, leading to a cost overrun on this item.

Unfamiliarity with differences regarding equipment and material requirements between standards can also lead to “technically inappropriate procurement scheme” and “choosing inappropriate suppliers” (see Figure 5). This sometimes cause disputes between contractors and consultant engineers regarding procurement schemes. For instance, in a project in Malaysia which adopted ASTM standards, the Chinese contractor had not identified the differences between Chinese and ASTM standards, and purchased the steel plates from Chinese suppliers. According to the contract, the steel plates should meet the requirements of ASTM A20/A20M-2017 (Standard Specification for General Requirements for Steel Plates for Pressure Vessels), which has different parameters from Chinese standards, and the consultant engineer refused to approve the acceptance of the procured steel plates. In order to reduce loss, the contractor devoted a large effort to compare the requirements of material parameters in both standards through calculation and analysis, and demonstrated that those steel plates purchased from Chinese suppliers could meet the requirements of the ASTM standard. Although the procured steel plates were finally accepted by the consultant according to the results of comparison, unfamiliarity with the difference between the Chinese standard and the ASTM standard still caused a construction delay, as well as additional resources in comparing the standards.

(5) Construction problems related to unfamiliarity with differences of standards

“Construction cost increasing” obtains the second highest score among all problems (see Figure 5), showing that under the condition of unfamiliarity with the differences between standards, Chinese contractors had to spend more during project implementation. For example, in a project in Ecuador that adopted ASTM standards, the Chinese contractor

was unfamiliar with the differences of steel bars, and used equipment that matched the Chinese standards to process the steel bars produced in accordance with ASTM standards, resulting in cracks when bending the steel bars. In order to solve the problem, the contractor modified the equipment to adapt to the characteristics of the steel bars, which resulted in “construction cost increasing”, as well as “construction delay”.

“Improper construction method” is another important issue that should not be neglected in delivering international hydropower projects (see Figure 5). Due to different application conditions, international standards sometimes have different requirements for construction processes, which can lead to contractors using improper construction methods that follow the experience in delivering Chinese projects. For example, in the project in Fiji that adopted AS/NZS standards, because the project is located near the sea with relatively higher environmental chlorine ion content than the contractors’ delivered Chinese projects (mainly located inland), the requirements of steel plates regarding erosion resistance were higher than that of Chinese standards. The Chinese contractor lacked such experience in dealing with this circumstance, and the construction method submitted by the installation team of the contractor was revised many times, which affected the construction progress, and caused a construction delay.

5. Application of the Analytical Framework: A Case Study from Nadarivatu Renewable Power Project in Fiji

(1) Project profile

The Nadarivatu Renewable Power Project, located in Fiji, consists of a 43 m high and 90 m long concrete gravity dam, a 2 km long water intake tunnel, a 2 km long pipe, a power plant, and a power transmission and transformation system. The project was delivered with an EPC contracting method. The owner is the Fiji State Electricity Bureau, the consultant is a New Zealand consultant company, and the EPC contractor is a Chinese company. The Australia/New Zealand (AS/NZS) technical standards used in the project were new to the contractor, as delivering this project was the first job in the Oceania market for the contractor. The Chinese contractors encountered a series of problems due to unfamiliarity with AS/NZS standards, which can be illustrated by the analytical framework for technical standards (see Figure 1).

(2) Problems related to calculation methods of standards

The differences between the calculation methods of AS/NZS and Chinese standards are reflected in the design of the pipeline. The contractor requested to use the software based on the Chinese standards, whereas the consultant requested to use the software according to the AS/NZS standards, as the two software follow different calculation methods. Although the outcomes of calculation using different software are similar, the contractor still could not convince the consultant, and had to learn and use the software that they were unfamiliar with.

(3) Problems related to equipment requirements of standards

Compared to the Chinese standards, the AS/NZS standards have stricter requirements on the equipment control system, ventilation system, fire-fighting system, pipeline system, and power transmission and transformation system design. For example, in terms of the control of flood discharge facilities, it is required that the power should be supplied not only from the power grid, but also from the local diesel generator. In addition to the sluice gate hoist being equipped with a diesel-motored pump, the crawler crane was also required to be able to open and close the sluice gate. These measures are much more redundant than the requirements of the Chinese standards.

(4) Problems related to Construction methods of standards

The differences between the construction methods of AS/NZS and Chinese standards can be demonstrated by the installation of the pipeline. The pipeline of the Fiji project adopts an ASTM A517 steel plate that is a high-strength steel, which should carefully avoid cold cracks and reheat cracks in the welding process. The consultant was required to process the heat treatment on the steel bifurcated pipe both before and after welding. However,

the contractor had no experience in the heat treatment of ASTM A517 after welding, and the installation measures were declined by the consultant many times. Finally, the contractor undertook the heat treatment before welding, and hired a New Zealand installation company to complete the heat treatment after the welding of the steel bifurcated pipe.

(5) Problems related to application conditions of standards

The differences between the application conditions of AS/NZS and Chinese standards can be illustrated by the requirements of the wind load of the power transmission and transformation system. Fiji is located in the Oceania region, and significantly suffers from typhoons. The AS/NZS standards require the power transmission and transformation system to resist a wind load of 90 m/s, whereas the requirement of Chinese standards is 38 m/s. In dealing with this significant challenge, the contractor hired a local consulting company that has rich experience in design to complete the design work according to AS/NZS standards.

6. Discussion

Hydropower project contractors are facing a greater challenge in international markets than in domestic markets due to using different technical standards [7–11,15]. In dealing with this, an analytical framework for technical standards has been established, displaying the key factors to measure the differences between Chinese and international technical standards. The results of this study illustrate how technical standards originating from different countries are substantially different in multiple aspects, and can significantly affect the success of an international project [13,19,26].

Fish conservation is considered an important issue when delivering a hydropower project [46]. A philosophy of standards in the analytical framework (see Figure 1) can well-demonstrate the differences between Chinese and international standards regarding the protection of fish. The construction of a dam or weir is usually required in a hydropower project, which creates obstacles to the movements of fish [47]. The Chinese standards and international standards agree on maintaining the biodiversity and resilience of the ecosystem [48–51]. The structure “fish lift” is widely used in hydropower projects in Europe and the USA as a promising solution to maintain fish passability for obtaining stable fish populations [47]. Similarly, many hydropower projects in China, with dams’ heights ranging from 3.0 m to 94.5 m, have built a variety of fishways to mitigate the impacts of barriers on migrating fish [52]. However, for some hydropower projects with high dams, where there are difficulties in fishway construction, the Chinese standards allow a different philosophy by building fish-breeding bases that ensure the fish populations remain at the same level as before [53]. For example, the fish-breeding base (see Figures 6 and 7) in the Yangfanggou Hydropower Project, with the dam’s height of 155.0 m, was built and run before the completion of the project.



Figure 6. Layout of the fish-breeding base of the Yangfanggou Hydropower Project.



Figure 7. The outdoor eco-imitation pool of the fish-breeding base of the Yangfanggou Hydropower Project.

The Yangfanggou Hydropower Project is located in the branch upstream of the Yangzi River. The fish-breeding base of the project occupies an area of 43,300 m², consisting of one workshop, fifty-three indoor pools, and three outdoor eco-imitation pools for fish-breeding (see Figures 6 and 7). More than 500,000 fish of different kinds are bred and released to the river every year for the conservation of biodiversity.

The Chinese contractors need to understand the differences of standards originating from various countries, which will help balance the relationship among safety, economic, environmentally-friendly, and applicability principles in delivering international hydropower projects. Practical strategies for reducing the impacts of problems related to the differences between Chinese and international technical standards are as below:

- (1) The survey results (see Figure 3) demonstrate that there are differences in all aspects between international and Chinese standards, and there is a need to compare the standards originating from different countries/regions. Understanding philosophies of different standards can help identify the trends for the development of standards by optimally balancing safety, economic, environmentally-friendly, and applicability principles. Contrasting the logic structure of different standards can assist in examining the completeness of the standards, and this can facilitate mutual recognition of the standards from various countries/regions, thereby maximizing the effectiveness of global resources such as expertise, technologies, methods, and products. Comparing different standards on calculation methods, equipment and material requirements, test methods, and construction methods can help in learning the features, strengths, and weaknesses of the standards, and then in the appropriate application of the standards in matching with local conditions to fulfill design, procurement, and construction tasks in international hydropower project delivery.
- (2) As the problem of applying international standards is a critical issue (see Figure 5), and is closely related to all aspects of international hydropower project delivery (see Figure 4), it is essential to improve the contractors' capability of using international standards. Conducting comparative studies between Chinese and international standards, case studies on using international standards, transferring tacit knowledge into explicit knowledge on standards, and training activities are necessary to enhance both organizational and individual capabilities in applying international standards.
- (3) Since design problems, such as low approval rates of design products, design delays, design errors/defects, and design options being not cost-effective, are strongly related to unfamiliarity with the differences of standards (see Figures 4 and 5), the contractors should cooperate with both project consultants and experienced international designers. Open communication is essential to ensure that the requirements of consultants, and the intentions of contractors, can be accurately and quickly circulated without being misunderstood. To meet the key design challenges in using international stan-

dards, the contractors can hire experienced international design subcontractors, and collaboratively fulfill technically and financially feasible designs. The interviewed managers confirmed that, although experienced international designers may charge more than Chinese designers, their expertise on using international standards and their familiarity with local project environments can bring more cost-effective design options, leading to significant project cost reductions.

- (4) To avoid the procurement problems (see Figure 5), contractors should clearly understand the requirements of both international and Chinese standards. In preparing procurement schemes, contractors should take worldwide suppliers into consideration, as long as their equipment and material can meet project requirements, and then choose suitable suppliers to achieve cost-effective procurement.
- (5) To avoid construction problems, such as improper construction methods, construction costs increasing, construction delays, and poor construction quality (see Figure 5), on one hand, contractors need to understand the key differences between international and Chinese construction standards, and, on the other hand, they should take full advantage of the expertise accumulated from Chinese projects, thereby improving the efficacy of construction.
- (6) As integrated project management is a key issue arising from the problems of applying international standards (see Figures 4 and 5), contractors should emphasize the coordination among standards of design, procurement, and construction. For instance, in the design process, contractors need to appropriately consider equipment functional requirements, material processing restrictions, and constructability in accordance with relevant international standards, thereby achieving optimum designs.

7. Conclusions

Overall, on the basis of the analytical framework for technical standards (see Figure 1), the differences between domestic and international standards, and their impacts on international hydropower project delivery, have been clearly illustrated, with support of the data collected from Chinese contractors. As shown in the analytical framework for technical standards (see Figure 1), the differences between domestic and international technical standards can be measured by eight essential factors: philosophy of standards, logical structure of standards, completeness of standards, calculation method of standards, equipment and material requirements of standards, test method of standards, construction method of standards, and application conditions of standards. The survey results (see Table 3) show that American standards (ASTM, ACI, ASME, IEEE, ASCE, AASHTO, USACE, and USBR), European Standards (EN, BS, DIN, and NF), ISO standards, and Chinese standards have been widely used in the construction industry worldwide. The survey outcomes (see Figure 3) demonstrate that differences exist in all of the above aspects between Chinese and international technical standards. Notably, the difference of “philosophy of standards” ranks first, and this illustrates that the safety, economic, environmentally-friendly, and applicability principles of technical standard systems from various origins can have significant differences.

Hierarchical cluster analysis (see Figures 4 and 5) reveals that unfamiliarity with differences between domestic and international technical standards can cause multiple problems during international hydropower project delivery, which can be classified into five groups: problems of applying international standards, integrated project management problems, design problems, procurement problems, and construction problems. These technical standard difference-related problems have deep impacts on international hydropower project quality, cost, and time performances. Unfamiliarity of differences between domestic and international standards can lead to technically and/or financially uncompetitive designs, and can also result in the procured equipment and materials from domestic suppliers not meeting the requirements of international standards. Due to different application conditions, international standards sometimes have different requirements for construction processes, and this can cause contractors to use improper construction methods that

follow their experience in delivering domestic projects. Unfamiliarity with the differences between domestic and international standards is also a key barrier for coordinating design, equipment procurement, and construction activities.

The above findings suggest a clear need for contractors to systematically understand the differences between domestic and international technical standards to improve performance in international hydropower project delivery. Practical strategies for reducing the impacts of problems related to differences between standards include: (1) a comparative study of the standards originating from different countries/regions; (2) case studies on using international standards, and training for enhancing organizational/individual capabilities; (3) cooperation with consultants and international designers for better designs; (4) choosing suitable suppliers worldwide by understanding the requirements of both domestic and international standards; (5) taking advantage of the expertise accumulated from domestic projects in international hydropower project delivery; and (6) emphasizing the coordination among standards of design, procurement, and construction for improving integrated project management.

The main limitation lies in the fact that the data of this study were collected from Chinese contractors. However, the research questions can be extended to different regions, and the viewpoints of this study can be tested in future research by collecting data from different participants and broader areas worldwide. Future research should further study the aspects within the analytical framework regarding technical standards' differences on philosophy, logical structure, completeness, calculation method, equipment and material requirements, test method, construction method, and application conditions. How these differences between domestic and international standards may interrelate with each other and have influences on international hydropower project delivery should be emphasized in further research.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/w14040662/s1>, Questionnaire: Questionnaire on the application of Chinese and international technical standards in international hydropower projects.

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