

Study on Seismic Design and Behaviour of the Integral Abutment

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Abstract. The integral abutment bridge (IAB) has been regarded as an efficient and effective seismic design in bridge structures by many civil engineers in recent years. In this paper, some advantages of IAB are shown. By comparing with the traditional abutments, the design of IAB can save the cost of those expansion devices in both the construction phase and maintenance phase. Moreover, the seismic performance of IAB is proved to be better for its unique advantages such as increasing integrity by cancelling the expansion joints and bearings, reducing the backfilling pressure, and limiting the rotation. Therefore, the application of IAB has been spread in many countries, especially in America. However, this paper also conducts some problems in the field of IAB which can be regarded as the potential research direction. The first is the delay of IAB's application in China and the corresponding urgent requirement. The second is the absence of a unified specification. And the last is that the advanced-performance piles in the integral abutment are expensive. The information presented in this paper aims to help arise and expand the relative emphasis and research in the field of IAB.

Keywords: Integral abutment, Traditional abutment, Seismic performance, Backfilling.

1. Introduction

Earthquake, a type of natural disaster, has been regarded as a global challenge due to its destructiveness and unpredictability. Thus, the structural engineers are asked to consider the corresponding aseismic design to eliminate or minimize the extent of the failure of the structures. For bridges, the seismic distresses can be categorized into five groups according to the corresponding components: (a) distress on the girder, (b) distress on the bearing, (c) distress on the piers, (d) distress on the foundations, and (e) distress on the abutment [1]. This paper will mainly focus on abutment by introducing the integral abutment.

The bridges with integral abutments are called the Integral Abutment Bridges (IAB). The most apparent difference between the traditional abutment and the integral abutment, from the perspective of the profile, is the connection between the girder and the abutment. As shown in Figure 1, in the bridge with the traditional abutment, there is an expansion joint at each end to avoid irregular thermal cracking while serving and a bearing on the top of the abutment carrying the girder. On the contrary, Figure 2 shows that both the expansion joints at the connection and the bearings are removed in the bridge with the integral abutment and the girder and the abutments can be regarded as an integral structure. Without expansion joints, the whole structure will displace back and forth to the road on land under the traffic load and environmental loads [2].

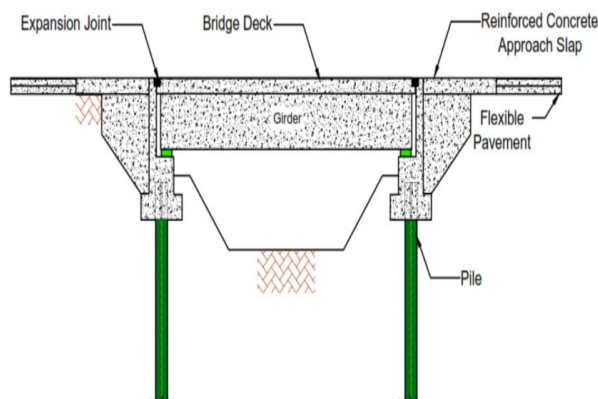


Figure 1. The example of the traditional abutment bridge [3]

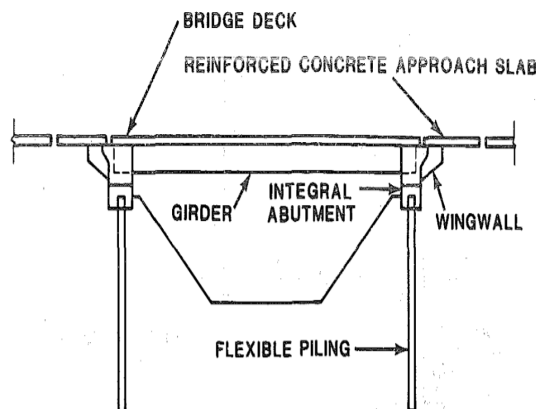


Figure 2. The example of the integral abutment bridge [4]

The integral abutment has been widely concerned due to both the serious problems brought by the expansion devices in the bridges with the traditional abutments and the better seismic performance of the integral abutment with an efficient economy. From the aspect of expansion devices, many reports pointed out the likelihood of destruction because of the erosion brought by the water and salt [5, 6]. The data in the surveys from different countries can prove the statement. For instance, in America, the number of bridges whose expansion joints were damaged accounted for over 20% of the total number of bridges once [7]. And in China, there were 286 bridges in which the penetration phenomenon occurs on the joints in Hebei Province while a total of 614 bridges were investigated [8]. Thus, many engineers state that it is necessary to push forward the removal of expansion joints and apply the integral abutment.

However, currently, there has not been a formal and unified specification about integral abutment design yet. Besides, the development of IAB is relatively delayed in some countries which might cause an amount of waste in construction and maintenance and some safety hazards, especially in the earthquake zone. Therefore, this paper aims to review the current research on the seismic design and behaviour of IAB to arise the focus on the application of IAB. In this study, the worldwide application will be shown first. Then the better seismic performance of IAB will be indicated by comparing it with the traditional abutment. At last, some details in the seismic design that interest many researchers will be explained.

2. Worldwide application of the integral abutment bridge

According to the previous research, the relevant official document about the application of the IAB in Germany in 1999 can be found and the study of it in China can date back to the end of the

20th century [9, 10]. Besides, Chen et al. [10] also stated that the history of IAB can date back to the 1920s. Thus, in this section, the general worldwide application of IAB will be discussed from the perspective of America, Europe and China respectively.

As aforementioned, the study of IAB in America is relatively early. According to the report made by Akhnoukh et al. in 2021 [11], the number of bridges with fully integral abutments exceeded 9000, not to mention the bridges with semi-integral abutments the number exceeded 4000. On the other hand, the extent of the American government's emphasis on IAB can be reflected by the following data. There are still over 90% of states where the joints would be cancelled as much as possible for the construction of the IAB and over 77% of states where the new bridges would be designed as fully integral abutment type or semi-integral abutment type as much as possible.

Compared with the application in America, the practice of IAB construction in Europe is less, but the governments are taking a positive attitude towards it and some engineer representatives have indicated that IAB should be regarded as an alternative when designing [2, 9]. Some design details are different in those European countries because of the lack of a formal and unified design specification. According to the survey, the design details can be analysed from these aspects: foundation requirements, backfill, approach slabs, wingwalls, beam design and curved geometry [9]. For instance, White et al. [9] stated that while choosing the type of piles which are set beneath the abutment, the most common type chosen in Europe is the large diameter steel pipe piles with the core of the reinforced concrete, unlike the situation in the America where the H-piles are chosen most frequently.

By contrast, the research and application of IAB are relatively scarce in China, as shown in Figure 3, and it seems like IAB has not been regarded as a worthy alternative in the general construction of new bridges or seismic design. According to the research, as of 2016, there were only 57 integral bridges, taking into account both those that had been constructed and those that were designed [10]. While the proportion of fully IAB and semi-integral bridges in Switzerland exceeded 40% [10], considering that the total number of highway bridges exceeded 8 hundred thousand in 2016 in China [12], IAB only accounted for less than 0.007%. And from the seismic perspective, some researchers recommend some earthquake isolation and reduction devices such as sliding friction bearing and flexible rubber bearing [13] instead of the integral abutment.

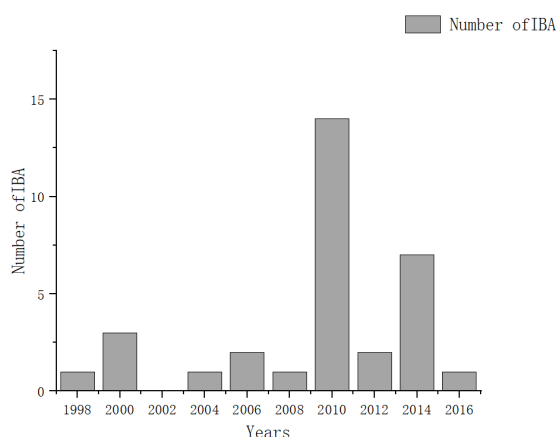


Figure 3. The IAB in China [3]

3. Comparison of seismic performance between the integral abutment and the traditional abutment

Conventionally, the seismic design idea can be categorized into two aspects, seismic ductility capacity, and seismic reduction and isolation system [1]. Applying these two ideas to traditional abutment designing, the former requires the abutment to resist the earthquake load through elastic deformation instead of failure to reduce the damage and the latter main asks to apply some bearing

technology such as laminated rubber bearing and pure sliding friction bearing to either consume the inputting earthquake load or isolate and prevent earthquake load from transmitting to the structure. For instance, laminated rubber bearing can guarantee that the relative movement between the girder and abutment can occur under the earthquake load to achieve seismic isolation to the bridge substructure [13].

The seismic effect of the traditional abutment can be proven by several earthquake cases. For instance, in the East-Japan Earthquake which occurred in 2011, as shown in Figure 4, even though the magnitude of the earthquake reached 9.0, many bridges still survived for the reason of bearing elasticising since the 1995 Kobe earthquake [14]. However, the defects of traditional abutment remain serious. Shi et al. [13] indicated that the rubber bearings on the abutments have a weaker ability in resisting tensile force which is usually brought by the vertical earthquake load. But some specifications like Chinese specifications assume that the vertical load is not necessary to check [15], which might lead to a blind area in designing seismic bearing. The report also stated that those bearings might not survive the near-fault earthquake since the tremendous energy cannot be absorbed and eliminated by the bearings in a short time [13]. The earthquake that occurred in Qinghai Province, China in 2021 can prove this statement. The girder of the Yematan bridge, which is near the earthquake fault, struck the north abutment and fell as shown in Figure 5 [16].



Figure 4. Sendai Bridge and its bearing [8]



Figure 5. The collapse of Yematan Bridge [16]

For the integral abutment, the most significant advantage in the seismic aspect is that the absence of expansion joints and bearing increases the stiffness and strength of the whole structure. Compared with the traditional abutment, the more advanced seismic performance of the integral abutment has been proven by experiments [17]. Despite having unique functions and earthquake-resistant ability to some extent, the expansion joints and bearing in the traditional abutment still can be regarded as the weak parts in the earthquake which possibly bring safety hazard effects [18]. Additionally, another reason for some researchers who are not welcome the traditional abutment is that the application of new types of bearings will significantly increase the construction cost [19]. And that problem is solved in the integral abutment design.

Even though the relevant design specifications have not been completed yet, many research reports point out that one of the most main parameters needed considering is the effect of backfilling soil [3, 18]. The integral abutment will displace back and forth together with the girder in the earthquake, increasing the interactive effect with the backfill soil which might result in a significant change of the stress in the abutment. But Erhan and Dicleli [17] stated that the passive soil pressure in the traditional abutment was even larger than it in the integral abutment because the integral connection allowed both two abutments in IAB to resist the seismic load together. Additionally, during the earthquake, the integral abutment will perform better in limiting the rotation than the traditional abutment because

of the lateral restraint deficiency and the larger inertial force effects caused by the taller and heavier abutment [17, 18].

4. Details of the integral abutment design

There are some aspects needed considering while designing, especially in the seismic design, on which the agreement has been raised among many researchers. In this section, the analysis can be divided into 2 aspects: backfill and the piles of the abutment. Details are as follows.

4.1 Backfilling

As aforementioned, many engineers indicate that backfill should be regarded as one of the crucial design points. On the one hand, these cyclic displacements will affect the internal stress of the backfill leading to the change of the stiffness, especially under the rare earthquake action [20] which might reduce the support to the abutment. On the other hand, this type of “compaction” will cause the settlement of the backfill and then the approach slab connecting the road on land and the bridge might crack [8, 11, 18].

To mitigate this problem, first, the total length of the bridge should be restrained to reduce the inertial force in the structure and the backfill soil pressure. But in other words, it is also a disadvantage of IAB that it is only suitable for medium and small span bridges and according to the research the maximum length of IAB is around 457m [18].

Then, the problem might also be solved by changing the type of backfill soil. Some researchers state that using some elastic materials can reduce the settlement of the backfill and avoid the increment of the stress, such as the expanded polystyrene geofoam recommended by Horvath [21]. And others prefer reinforced materials like geogrid [22]. However, some researchers put forward some opposite opinions for the former method. For instance, the experiment showed that the integrity would be reduced by the geofoam materials and led to the larger maximum moment and abutment deformation with lower horizontal constraint [23]. And the data also showed that the latter method, using reinforced materials, would resist the tensile force and reduce the maximum moment in the abutment during the earthquake and have a better seismic performance [22, 23].

4.2 Piles of the integral abutment

A consensus has been achieved to construct the piles beneath the integral abutment to increase its flexibility, as shown in Figure 6. As mentioned before, the preferences of types of piles in each country are different. For instance, the prestress concrete pile is the most used in China. However, it is indicated that the problem of the lack of flexibility is still existing in the concrete piles and the cyclic loadings might cause cracking [8, 10]. Considering several factors like the seismic stress response and orientation, the steel pipe pile has relatively outstanding properties. The experiment showed not only its ability to reduce the abutment displacement and moment which was similar to the H-pile but also its superiority in neglecting the direction of the seismic load with the same flexural rigidity in each orientation which was just the drawback of the H-pile [8]. But the cost of the steel pipe pile is relatively high.

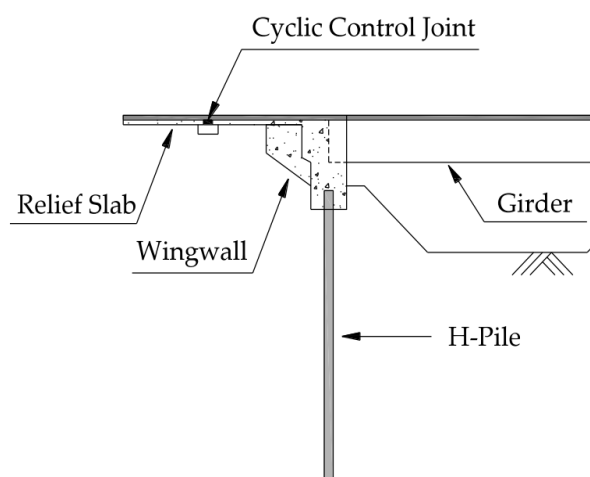


Figure 6. The pile beneath the integral abutment [20]

Additionally, the joints of the integral abutment and piles also concern some researchers where the bending moment will increase significantly during the earthquake due to the displacement of surrounding soils. The traditional dealing method is to embed the piles into the abutment directly but the disadvantage is apparently. It will increase the stiffness of the joint and decrease the deformation capacity and the base of the piles is more likely to break due to the tremendous stress level.

The improvement methods can be divided into three different ways, deepen the buried depth, add pile sleeves and strengthen the joints. Chovichien [24] recommended preventing the fatigue failure caused by the local buckling and applying the H-pile bending to its minor axis to decrease the stress level at the joints. An experiment also proved that the seismic performance of the abutment-pile joint can be improved by adding the spiral stirrups on the top of the piles and increasing the buried depth [25]. And Ahn et al. [5] preferred to add the reinforcement steel on the joints to resist the deformation.

5. Conclusion and future work

This paper mainly discusses the seismic performance of the integral abutment and some of its design details concerning the earthquake circumstances. Firstly, the paper states the recent common emphasis from civil engineers on applying the bridges with the integral abutment. The data also proves its rapid development in each region, though there are some slight differences in application progress. Then the better seismic properties of the integral abutment are shown by comparing it with the traditional abutment. Applying the expansion joints and bearings or not is the most crucial reason resulting in the different seismic performance. Those new types of expansion devices which are regarded as earthquake-resistant designs in the traditional abutment may still not be competent and they might fail first in some extreme conditions. Facing a near-fault earthquake can be regarded as an example. Meanwhile, the integral abutment might be superior as well when dealing with the problems such as backfilling soil and limiting the rotation. The last part of this paper explains two of the most concerning design details of the integral abutment in the seismic aspect. The first is backfilling soil problem and three prevailing solution plans are limiting the length of the girder, applying the elastic materials and using the reinforced materials, among which the experiments proved the last one is more reasonable. The second is the piles of the integral abutment. In the designing phase, engineers should determine not only the types of the piles to increase the abutments' flexibility, but also the dealing method of the joints of the integral abutment and piles to avoid premature failure under the seismic load.

However, some explicit and potential problems in this field can also be concluded. The lack of emphasis on this area in China is apparent. Not to mention the huge sum of annual cost maintaining expansion devices on nearly a million bridges, the situation that a large amount of domestic area is in the earthquake zones asks for more advanced seismic properties in bridges, for example, applying the

integral abutment. The earthquakes in Sichuan province and Qinghai province can show the urgency of this requirement. Then the stagnation of putting forward a unified design specification is a barrier to generalizing the integral abutment. Without the specification, the most lower construction companies may prefer to choose and design the bridges with the traditional abutment on which there are more systemic and complete specifications. Additionally, the relatively higher cost of steel piles, which have better seismic properties to increase the integral abutments' flexibilities, makes some engineers hesitate to choose. In order to spread the application of the integral abutment, this paper would like to put forward three corresponding suggestions. Firstly, the government should pay more attention to the integral abutments' cost efficiency and eminent seismic performance. Secondly, the international academic field needs to work for a unified and systemic specification and each country can reference it and establish individual specifications respectively. Last, material researchers might focus on the replaceable cheaper materials with the same or even more advanced properties than the steel piles.

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