Design of a Self-lifting Pedestrian Bridge for Flood-Prone Locations

B. K. Mathew, S. Lakshmi, and G. Hari

Abstract Global temperature has shown instantaneous and vigorous rise since past decade with temperature rise by about 1.71°F. Its effects have also been disastrous. Climatic change and higher floods have been visible since few years. Kerala also got affected by massive flood since last two years. This has led to destroy of about 16,000 km PWD road, 82,000 km local road and 134 bridges. This project includes a live project for Kottayam Municipality, i.e. a design of steel pedestrian bridge that has to be constructed against tributary coming from Meenachil River. Previously, a pedestrian bridge existed at this location which was washed away by the 2018 Kerala floods. An innovative approach to enable the bridge of lifting itself when the water level rises beyond certain limits is proposed. The design of the bridge is done using STAAD pro. software, and the hydraulic lifting is explained numerically.

Keywords Pedestrian bridge · Steel bridge design · Self-lifting property · STAAD pro.

1 Introduction

A footbridge (also referred to as, pedestrian flyover, or pedestrian overcrossing) may be a bridge that is constructed for movement of pedestrians and also in some cases cyclists, animal traffic, and horse riders, but not for vehicular traffic [1]. In some cases, footbridges are also used to complement the landscape and for decoratively to visually link two distinct areas. In some of the poor rural communities inside the developing world, a footbridge could also be a community's solely access to medical clinics, markets and colleges, which might be inaccessible when rivers area unit is too high to cross [1]. Damages and failures of bridges are catastrophic events and involves large number of casualties. Environmental effects such as floods, earthquakes and heavy winds seriously affect bridges. Floods are a major reason in the failure of

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bridges. Global warming and the subsequent rise in surface temperature indicates that floods are expected to occur in every 1–30 years. During 2018 Kerala floods, about 16,000 km PWD roads and 82,000 km local roads and 134 bridges have been damaged. Bridges are designed considering all the factors but cannot be designed based on most severe conditions. So, innovations in the structures of bridge so as to make them safer and durable are essential. The main objective of this work is to design a pedestrian bridge capable of lifting itself when the water level crosses a prescribed limiting value. The objectives of this study include to propose a design of pedestrian bridge for Kottayam Municipality (Live Project).

2 Literature Review

Sandovič & Juozapaitis presented a new structural solution for pedestrian steel suspension bridges. It includes suspension members with bending stiffness and a pre-stressed tie connecting the outer supports connecting the central supports [2]. Foti et al. [3] addressed the dynamic behaviour of footbridge. Two scenarios, in free vibration and made vibration produced by a hard and fast number of pedestrians walking on the bridge at a particular speed and frequency, are tested. In each test, the effect on the comfort of the pedestrians, the natural frequencies of vibration, the mode shapes and damping factors are estimated. Sause [4] studied the application of I-shaped steel girders with tubular flanges in highway bridges to make use of their huge torsional stiffness. They identified that for straight girder bridges, the high value of torsional stiffness of a TFG model shows high value of lateral torsional buckling strength. Welch et al. [5] presents design of a pedestrian bridge over Coliseum Boulevard for the city of Fort Wayne, Indiana. A major obstacle for pedestrians south of the Indiana–Purdue University Fort Wayne (IPFW) campus is Coliseum Boulevard: a main arterial has an average daily traffic (ADT) of 50,000 vehicles. From the study, they concluded that arch type bridge is the most effective type of design suitable in that location [5]. Ali & Swarna present design of a pedestrian overhead bridge where the traffic exceeds more than 2500 vehicles for the elimination of conflicts between pedestrians and motor vehicles [1]. Wang et al. studied the dynamic response of a circular bridge pier forced simultaneously by earthquake and wave–current actions. On the basis of diffraction wave theory, the analytic solution for the diffraction of incident waves with uniform current on a circular pier is given. On the basis of the radiation wave theory, the analytic solution for the hydrodynamic pressures on a circular pier induced by combined earthquake and wave–current action is obtained [6]. Froli et al. present a selected concept named TVTδ (Travi Vitree Tensegrity) for lightweight long-span beam-like footbridges made from structural glass [7].

3 Methodology

The major objective of this work is to design of a pedestrian bridge and to incorporate self-lifting property into it. The work methodology included site visits at Thiruvathukkal, Kottayam Municipality and Irrigation department office for pre-design studies, data collection, topographical survey, questionnaire survey, design of self-lifting bridge and cost estimation.

The work began with an initial visit to the site and communication with the Municipality authorities. The proposed bridge is constructed at Kutitharaadi region of Thiruvarppu Panchayat, Illikal, Kottayam, Kerala. The visit to the site gave sufficient preliminary knowledge about the condition of the site and the limitations that have to be incorporated in the design. The aerial view of the site is shown in Fig. 1.

One bank of the proposed bridge is under Kottayam Municipality, and the other bank is under Thiruvarppu Panchayat. On communicating with the local people who are the beneficiaries of this work, it was able to know about the necessity of a bridge there for the public. The site actually had a wooden bridge for people's movement, which however got washed away in the last major flood of 2018 in Kerala. As a result, the people on both the banks of the river are experiencing difficulties in movement.

A bridge work was actually started in the area. However, that work was initiated without any preliminary investigations, soil testing or detailed and accurate design. On finding out these, the work was stopped immediately, and officials involved were also punished by the higher authorities. At present, the Kottayam Municipality requires a complete scientific study-based design approach for the bridge and thus contacted with the Civil Engineering Dept. of Saintgits College of Engineering.

Fig. 1 Site location

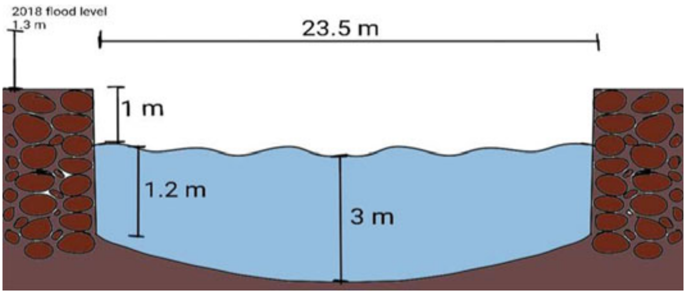

Fig. 2 Basic dimensions of the river span and depths

3.1 Basic Data Collected

The bridge site is about 42.979 m away from the nearby road. This access to the site is around 1.65 m wide. The river, which is a subsidiary of Meenachil River, is about 23.5 m wide at the site. Figure 2 shows the dimensions of width and depth of river. The river has a clear span of 23.5 m. The depth of river at centre is about 3 m and at the sides is 1.2 m at the normal water level in the river. The retaining wall on both the sides of the river is of RR masonry.

3.2 Hydrological Investigation

The recorded water levels of the tributary are as follows;

- Maximum Flood Level (MFL) = 1.3 m above ground level
- Normal Water Level (LWL) = 1 m below ground level

3.3 Topographical Survey

The preliminary site visit was followed by a detailed topographical survey. Total station survey was conducted and the site plan of proposed bridge site prepared. The prepared site plan is shown in Fig. 3. The width of the tributary is approximately 23 m long adjacent to which there exists narrow pathway of 2.5 m width (approx.) in either side of the tributary. A main road way having public transportation goes parallel to the tributary of width 4 m at a distance of 43 m from the one side of the channel. The details are as shown in Fig. 3.

Fig. 3 Site plan prepared

3.4 *Questionnaire Survey*

In order to know about the public demands regarding the bridge and to assess the necessity of a bridge, beneficiaries of the bridge were surveyed. This was also conducted to explore pedestrian satisfaction and safety preferences. An observational survey to obtain supplementary data to quantify pedestrian behaviour was also collected. People from all sections of the society and from all age groups were selected for the questioning. A questionnaire survey was conducted and about 20 responses from families in the immediate vicinity of the bridge were collected. People of both gender and different age groups were interviewed without partiality. Of all the people interviewed, 90% of pedestrians voted in favour for the construction of a new footbridge. When asked why, they were mainly concerned with the safety of their lives as well as their loved ones. They feared that the current setup is so dangerous that children cross the bridge holding a stretched tied rope and possibility to get drawn into the river is high. 8% of the target sample showed indifference. Furthermore, they argued that the establishment of a footbridge was unnecessary as it would only require common sense to cross the bridge carefully. 2% of the pedestrians was completely against the construction of a footbridge. When inquired, they suggested to depend on the two bridges on the either side of the current location which is 1.5–2 km apart. From the above results, it is evident that the majority of the target sample prefer to have a bridge exclusively for pedestrians, i.e. a footbridge. The graph showing the results is shown in Fig. 4.

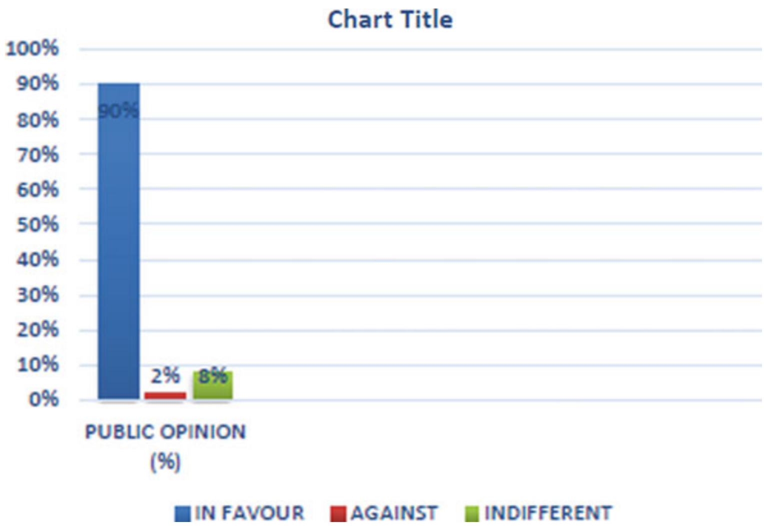

Fig. 4 Chart showing public opinion in survey conducted

3.5 Structural Analysis and Design

The details of structural design are as follows:

Dimensions
Span of the bridge in metres—24 m
Width of deck of the bridge—1.2 m
Height of truss—1.2 m
Dimension of slab panel—0.8 m x 1.2 m
Material Properties
Steel truss and chord members
Steel-concrete composite deck (Trapezoidal decking sheet PIL 44/130)
Load Calculation
Dead Load:
Weight of concrete = 1.92 kN/m
Weight of decking sheet = 0.08005 kN/m 3.
Floor finish = 0.4 kN/m
Therefore, total dead load = 2.40005 kN/m; Factored dead load = 3.24 kN/m
Live Load:
Pedestrian traffic load = 4.7088 kN/m; Factored live load = 7.0632 kN/m
Results Obtained from STAAD pro.
The results obtained after the analysis of the bridge in STAAD pro. is given below. The 3D rendered image of the bridge model is shown in Fig. 5.

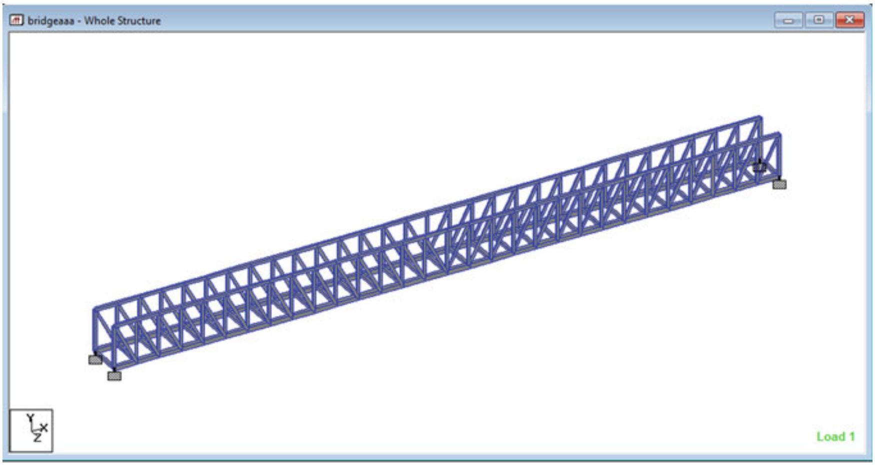

Fig. 5 3D rendered image of conventional pedestrian bridge

Support Reaction due to Dead and Live Load
The analysis gives the support reaction values at the four supports due to dead load and live loads as;

i) Due to dead load = 34.612 kN
ii) Due to live load = 36 kN

Deflection of Beam
Figure 6 shows the deflection of bean. It shows a deflection of 0.028 mm which is within the permissible limits.

Shear Force and Bending Moment of Beam

Figure 7 shows the shear force and bending moment of the beam.

Maximum Absolute Stress Values

Figure 8 shows maximum absolute stress values are seen in the support 32 and 94, and they are within the permissible limits.

Section Property of Beam

Figure 9 shows the section property of beam having the dimensions (80×40×4) mm.

It is known that the maximum permissible deflection of a pedestrian bridge is less than L/300. From the STAAD design, we have obtained a value 0.07 mm which is safe. The absolute stress values obtained show that high values of stress are obtained at the supports no. 32 and 94, and these are within the permissible limits. Utility check was also conducted for every member, and it can be concluded that no members fail.

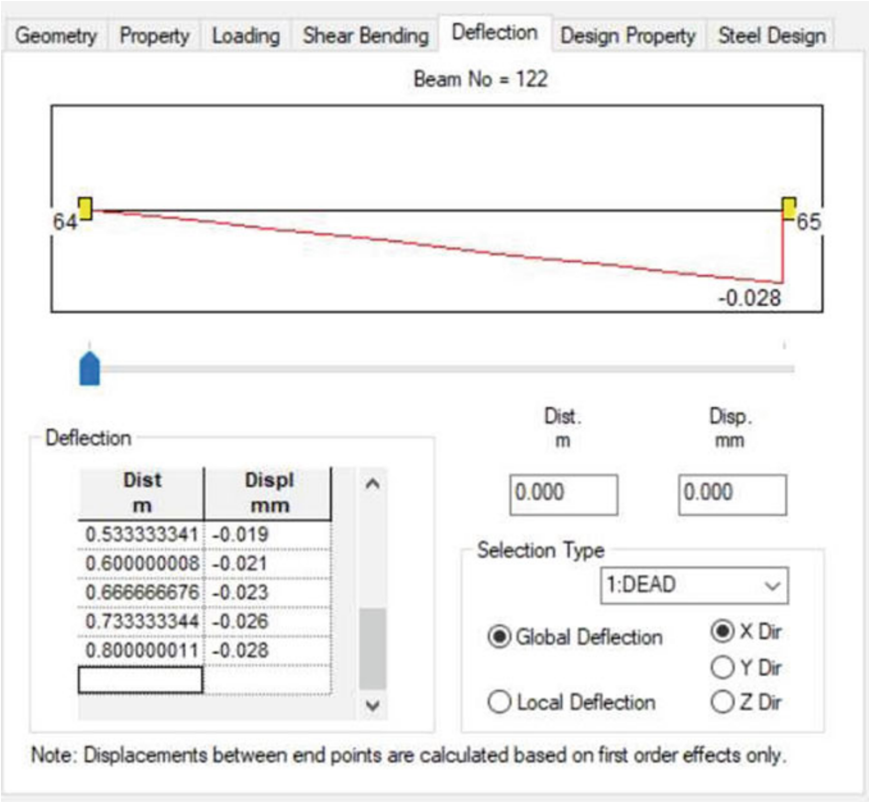

Fig. 6 Deflection of beam

3.6 Self-lifting Mechanism Design

Self-lifting, as the name suggest, is defined as the ability of an object to rise or elevate itself from a lower position to a higher position without using any external energy. Here, in our case, the pedestrian bridge is so designed capable of lifting itself upwards when the water level is above a prescribed limiting level from the base of the tributary. The basic principle of lifting mechanism is when the water pressure is more than the weight of the bridge including live load and provided sufficient base area, self-lifting property can be attained. Initial design calculations are carried out as shown below.

$$\text{Buoyant force(Uplift force)} = \rho_w \times V_{\text{sub}} \times g$$

$= 9.807 \times$ Area of base of column $\times$ height of water in column assuming a column of diameter 30 cm;

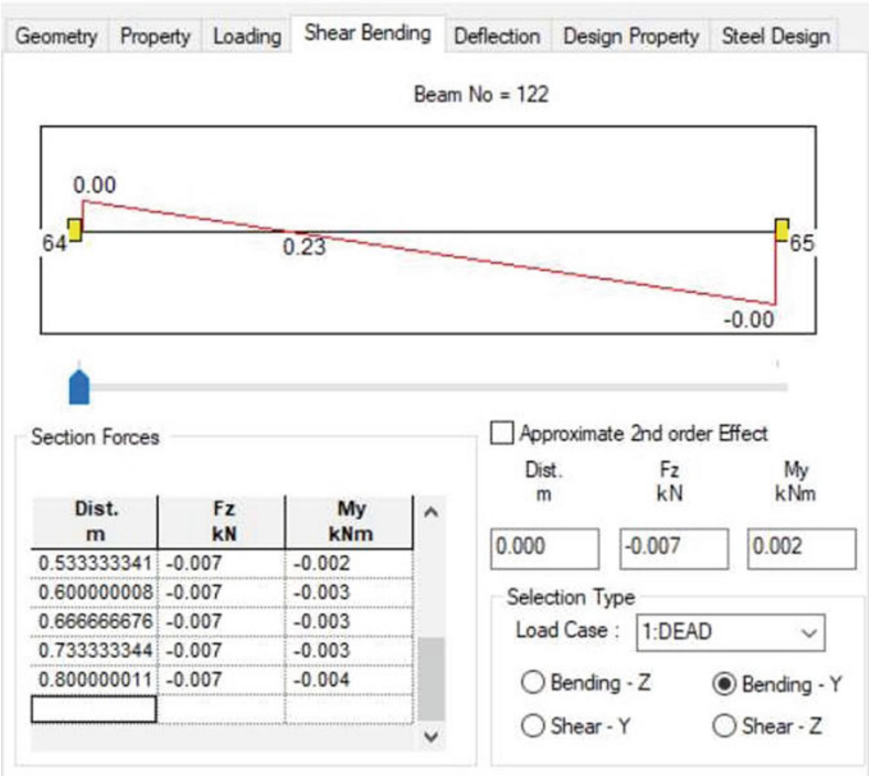

Fig. 7 Shear force and bending moment in beam

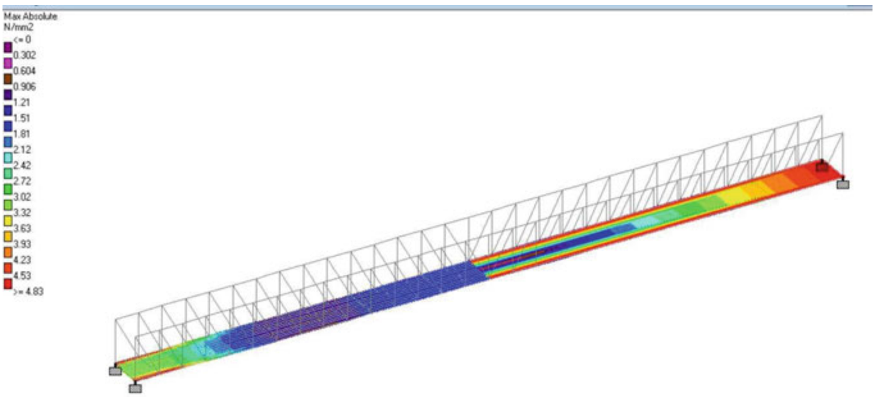

Fig. 8 Maximum absolute stress values

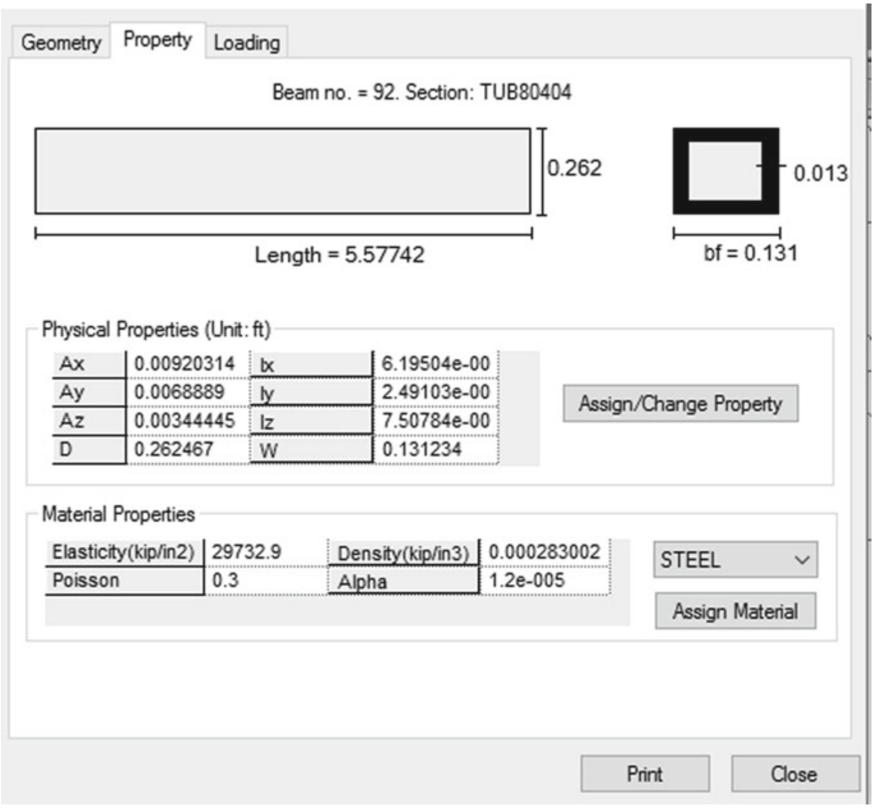

Fig. 9 Section property of beam

$$\text{Buoyant force(Uplift force)} = 9.807 \times {}^{\pi}/_{4} \times 0.32 \times hw \times 9.81 \qquad (1)$$

To lift the bridge, Uplift force >Weight of the structure including live loads (2)

From analysis of the super structure of bridge in STAAD pro., it was obtained that;
Support reaction in a single column due to dead load (DL) = 32 kN
Support reaction in a single column due to live load (LL) = 36 kN
Therefore, total load in a single column = 68–70 kN
Then, according to Eq. (2), 70 kN < Uplift force
i.e. $9.807 \times \pi/4 \times 0.32 \times hw \times 9.81 > 70$ kN
i.e. $hw > 10.239$ m

The requirement of bridge to be lifted must arise when the water level in the stream rises above 4 m. So, the bridge should begin lifting when the height of water

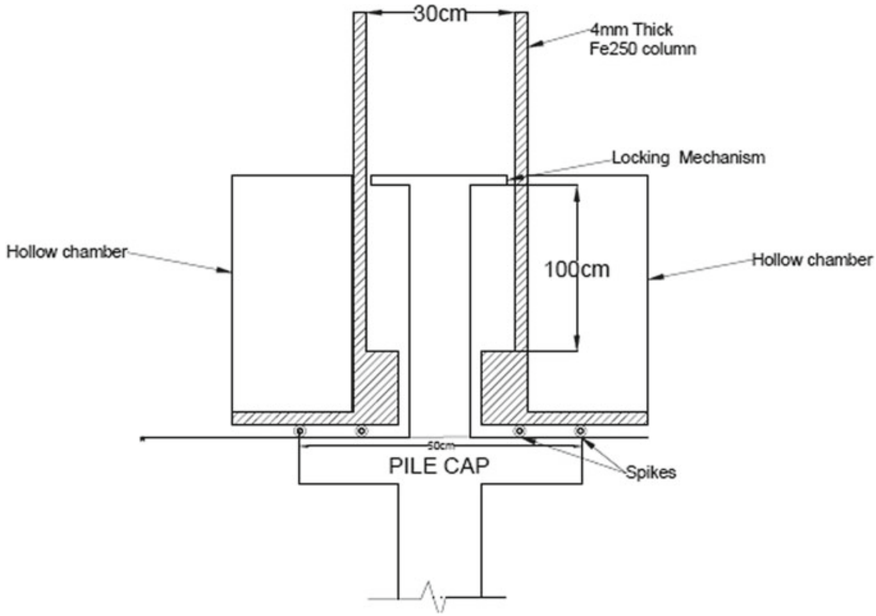

Fig. 10 Sectional view of the proposed lifting mechanism

in column is 4 m. The above obtained level of water required to lift the bridge can be reduced by increasing the diameter of the column. So, when $h_w = 4$ m Eq. (2) becomes $9.807 \times \pi/4 \times dc^2 \times 4 \times 9.81 > 70$ kN.

$$dc > 48 \text{ cm}$$

Therefore, adopt base diameter of column to be 50 cm.

The sectional view of the proposed lifting mechanism is shown in Fig. 10.

Various parts of the lifting mechanism and its functions:

Column: This is the most vital part in the lifting mechanism. The column should be able to withstand the load coming from the bridge and transfer it to the pile cap without undergoing buckling. So, the thickness of the column should be fixed based on this principle. Here, we have done trial and error method and adopted a column thickness of 4 mm of Fe 250 steel having a 30 cm dia. The column is also checked for a lateral load which is assumed to be 5% of the total load, and it was found safe.

Base area: This is very necessary for the lifting mechanism to occur. We fix the base area of the column such a way that enough area is available for water pressure to act on and the lifting to occur. In our case, we have done the numerical calculations and found out a base diameter of 50 cm is required for the lifting mechanism to activate. Spikes: Small projections are provided at the bottom of the base plate in order to improve water and base surface interactions. Along with that additional length extension projecting outward of the pile cap is provided for initial trigger of water pressure.

Hollow Chamber: A hollow chamber is provided around the area of base plate. This hollow chamber is made up of lightweight aluminium material. The main purpose of this chamber is to prevent water from entering the top of the base plate and which in turn makes way to exert more pressure at the bottom of the base plate.

Locking Mechanism: The locking mechanism is the most vital part which holds the cylindrical column from getting lifted away more than the required height. We can fix the height up to which we want to lift the bridge. In our case, we have fixed it to 100 cm as shown in Fig. 10. The locking mechanism is the extension of pile cap so is proposed to be made up of reinforced concrete.

Pile Cap: This member itself doesn't play any role on the lifting mechanism, but the whole mechanism is resting upon this.

Design Calculations

The factors that influence the bending behaviour in real columns are lateral loads, end eccentricity, column curvature and non-homogeneity of materials, etc. These factors should be given due consideration. Residual stresses, variation in inelastic stress–strain characteristics, shear strength, local buckling, shape of cross-section and end restraints are some factors that affect the buckling resistance of columns. It is impractical to involve all factors that affect the strength of column mathematically in any one formula. I.S: 800-1984 recommends the use of Merchant Rankine formula;

$$\sigma_{ac} = 0.6 \times \frac{f_{cc} \times f_y}{\left[f_{cc}^n + f_y^n\right]^{1/n}}$$

Check for Thickness of Column

Assume a cylindrical table of 50 cm base dia and 4 mm thickness. Let steel be of grade $f_y = 250$ N/mm^2.

Slenderness ratio, $\lambda = 1/r$

$$r = \frac{\sqrt{D^2 - d^2}}{4}$$

$D = 50$ cm
$T = 4$ mm$= 0.4$ cm
Therefore, $d = 49.2$ cm, $r = 22.27$ cm
$\lambda = (3.2 \times 103 \times 0.65)/22.27$
$= 93.39$
For $\lambda = 93.39$ and $f_y = 250$ N/mm^2, $\sigma_{ac} = 86.61$ N/mm^2
Load Capacity $= \sigma_{ac} \times \text{area} = 86.61[\pi/4(500^2 - 492^2)] > 75$ kN
$= 539.83$ kN > 75 kN

Therefore safe.

A 4-mm-thick Fe250 steel cylindrical column is adopted.

Working of the Lifting Mechanism

Various parts of the lifting mechanism and its roles were explained in the prior sections. Now, let us see how the lifting mechanism works. Figures 11 and 12 represent two different stages at which the setup rests. Therefore, this mechanism can be explained under two stages.

i) When water level is less than 4 m.
ii) When water level is more than 4 m.

i) When water level < 4 m

In this stage, the water level in the tributary will be less than 4 m that is a state there will not be sufficient water pressure to raise the column. In other words, the water pressure in this state is not sufficient enough to push and raise the 70 kN load coming from the bridge with the provided base area. Therefore, the whole setup remains at rest and no displacement occurs. Figure 11 shows initial position of the lifting mechanism.

ii) When water level > 4 m

In this stage, the water level is sufficiently enough to provide required pressure at the bottom of the base plate. At first, the pressure acts at the extended area which provides an initial thrust, and later, the pressure acts over the whole base area; thus,

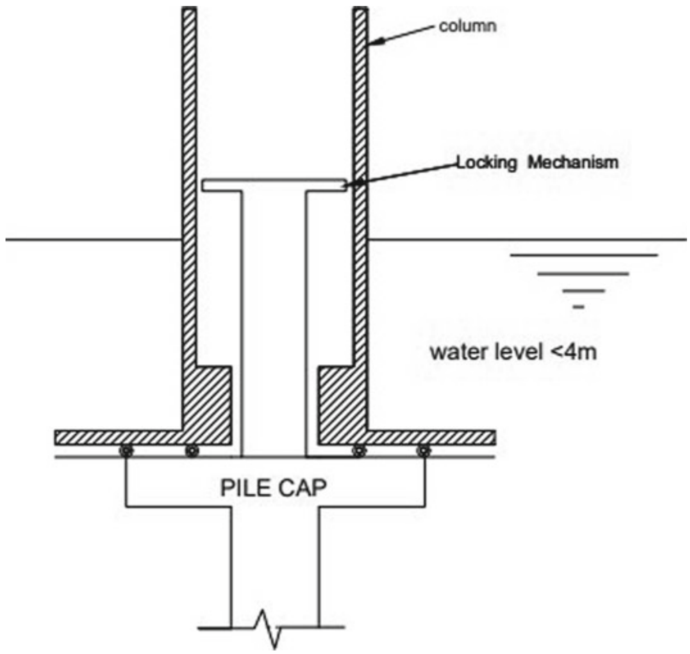

Fig. 11 Position of column when water level is less than 4 m

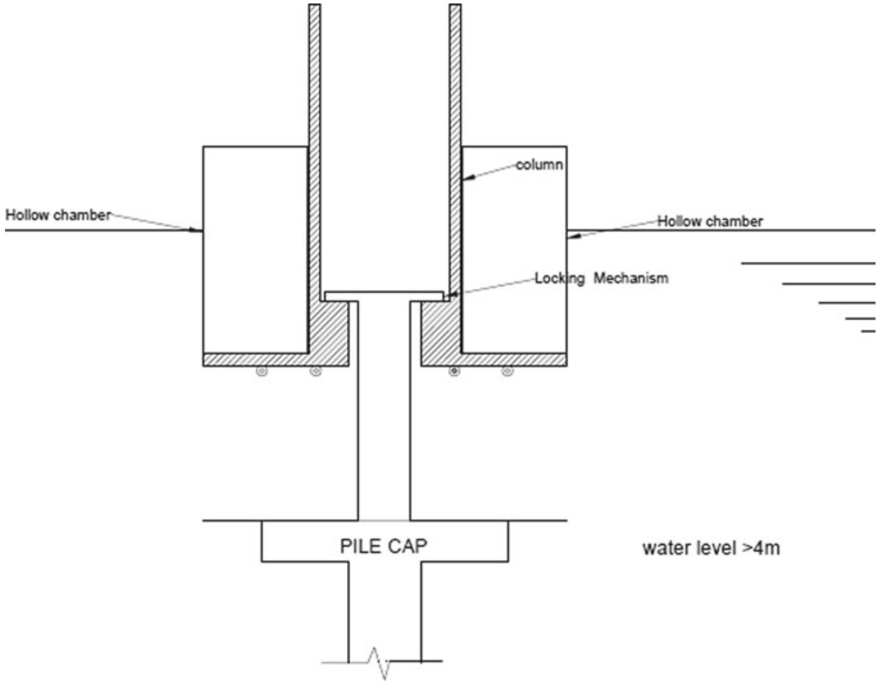

Fig. 12 Position of column when water level is greater than 4 m

more than enough force for uplifting is obtained. The column gets uplifted, and it reaches a position beyond which further lifting is not possible, i.e. at the locking mechanism. The bridge stays at the lifted up position till the water level remains above 4 m. Figure 12 shows the position attained by the column in this stage.

3.7 Stair Mechanism

Even though the bridge is expected to get lifted up in the most severe case of flood, the serviceability of the bridge is also considered in the lifted up position also. For this, the stair provided to enter the foot bridge is divided into two sections.

i) The fixed steps
ii) The movable steps

The fixed steps as the name suggest are fixed at the ground itself. We are providing a rise of 15 cm and tread of 30 cm for the steps. The movable stair portion is hinged at the entrance of the pedestrian bridge and is resting upon a vertical support over which it slides and increase the length when the bridge is lifted up. Figure 13 shows the stair setup. Initially, when the bridge is at rest, the stair angle will be 23°, and

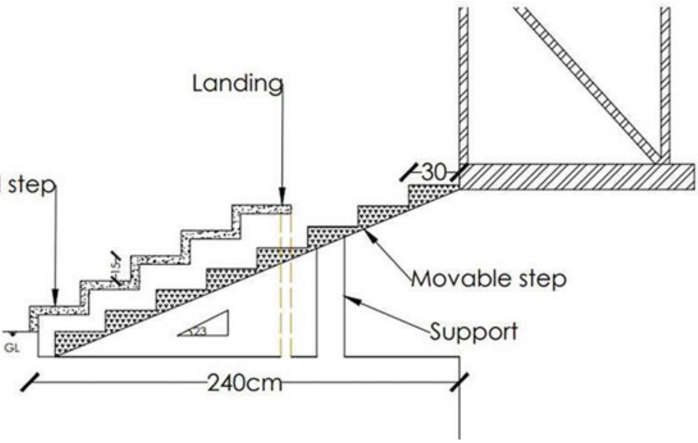

Fig. 13 Stair setup representation

when the bridge will be lifted up, the first flight of stair will have 23° inclination, and the next flight will have 60° inclination.

3.8 Cost Estimation

The total budgeted cost and its split up for constructing a pedestrian steel truss bridge incorporated with lifting mechanism at the proposed site is shown in Tables 1 and 2. From the tables, it can be seen that the total cost including all expenditures and overhead costs is Rs. 992,500/- only. The whole work is divided into two, i.e. superstructure and concrete work. The estimate for superstructure is as shown in

Table 1 Estimate for superstructure excluding concrete

Item/Description	Quantity	Rate (in rupees)
Steel (truss) @ 120/kg	3390 kg	406,800.00
Piers supporting bridge @120/kg	4847.11 kg	582,000.00
Hollow chamber @ 300/kg	27 kg	8,100.00
Decking sheet @ 56/kg	235 kg	13,160.00
Staircase steel	LS	20,000.00
Additional labour for lifting mechanism—10%		22,500.00
Overhead—10%		10,526.00
Unforeseen		6914.00
Grand total		1,070,000.00
Rupees ten lakhs and seventy thousand only		

Table 2 Estimate for concrete works

Item/Description	Quantity	Rate (in rupees)
Shuttering	LS	12,000.00
Piling @ 3500/m	80 m	280,000.00
PCC 1:4:8 @ 6600/m^3	2 m^3	13,200.00
Chipping and removing pile top	LS	7500.00
RCC 1:1:2 @ 15,570/m^3	0.50 m^3	7,7850.00
Columns for locking mechanism RCC 1:1:2 @ 13,710/m^3	0.10 m^3	1,371.00
Unforeseen		8144.00
Grand total		330,000.00
Three lakhs and thirty thousand rupees only		

Table 1. It includes the rate of materials required that is steel, aluminium sheets, decking sheets, labour charge for the construction, machinery cost and overhead of 10%. The labour charge is split into two as an additional skilled labour is required for the construction of lifting mechanism.

The estimate for the concrete is as shown in Table 2. It includes the works such as shuttering, piling, excavation, PCC, chipping and removing pile top, RCC, columns for locking mechanism and reinforcement. The expense for machinery and labour is calculated along with the works itself.

Total Cost estimate for the bridge is 1,070,000 + 330,000 = Rs. 1,400,000/-

The estimation is worked out for self-lifting pedestrian bridge based on standard procedures and rates. On comparing the rates, it can be seen that self-lifting pedestrian bridge incurs an additional cost of Rs.250,000.00 for including the lifting mechanism. Considering slight variations and fluctuations also, it will be less than Rs.300,000. Even though it seems that there is an additional expense, but it is not an amount which will make large difference in the total cost. The expense for lifting mechanism is less than or equal to 25% of the total cost of construction. By doing a benefit cost analysis, it can be noted that no more additional repair and maintenance charges including the construction of a new bridge are required. Also, the public importance of the structure is high. The increase in cost is not of higher value in terms of the serviceability and usability of the structure. Thus, the additional costs incurred are justifiable.

4 Conclusion

Amongst all the forms of travel and commute, walking is the most significant mode, and almost, everyone travels for at least about 5 h weekly by walking even in this age of advanced transport modes. In a country with large population, it is common to see more people walking on roads in both cities and rural areas. When large numbers of such people use roads, the environment and operating vehicles need to be safe so that pedestrians are not injured and killed. In this work, a self-lifting pedestrian bridge is designed. Initially, the design of a conventional pedestrian bridge is carried out. For this purpose, visited the Kottayam Municipality and Irrigation department and obtained the data on maximum flood level (MFL) as well as the low water level (LWL) and other data regarding the site. Topographical survey of the site was conducted, and a site plan was developed. Hydrological investigation of the tributary was conducted, and the details regarding the depth of water, high flood level were obtained. Questionnaire survey was conducted, and the relevance of the bridge was concluded; the mode of failure of the previous bridges was identified.

The design of steel pedestrian bridge was done using STAAD pro., and the economical sections were obtained. The results obtained from STAAD such as shear force bending moment, deflection and absolute shear are represented in the report. The design details were submitted to the department of works in Kottayam municipality. The self-lifting mechanism was incorporated with the steel bridge. The principle behind this mechanism was explained. The legitimacy of this mechanism was explained using analytical theories and numerical calculations along with pictorial representation. Various parts involved in the lifting mechanism were covered in detail.

Cost estimate of this project was prepared in a view to justify its requirement in long run and unforeseen floods to come and to prevent it from washing out. The cost turns out to be fourteen lakhs for total construction of the bridge. Inclusion of lifting mechanism has increased the rate of construction by 25%. But, this increase in the rate of construction can be ruled out in the long run considering the expenses caused for maintenance and repair of a conventional bridge which is often prone to get washed away.

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