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Research Article

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Rain and Snowmelt Augmented Design Flood for Highways Bridges in Snowy Mountains

Anand Verdhen*

Abstract

There is lack of codal and engineering practices to consider the rain mixed snowmelt induced flood flows for the design discharge in deciding hydrologic/hydraulic features of road/ highway bridges, resulting in varying degree of damages to structures and traffic movement. Synthetic unit hydrograph and watershed models are not suited to get reliable peak flood of numerous un-gauged catchments for concerned structures. The paper presents the methodology to consider the probable effective snowmelt and intensity collectively at desired return periods. Instead of neglecting the impact of melt-flow or just enhancing the design discharge by 10%, five options of peak runoff generating catchment criteria due to probable rain and/or snowmelt have been envisaged having rainfall intensity on time of concentration and melt intensity on degree-day melt index. Consequently, results of two small bridges, Wagund and Pernigaon located in Doda and Anantnag districts of J&K on NH1A using empirical, rational and slope-area methods have been presented. The peak design discharge computed was 395 and 71 cumecs at the Wagund and Pernigaon sites, respectively at 50 years return period during 2005-2009. Slope-Area method has been found useful to compute HFL for combined design discharge of snowmelt and rainfall, while Weir/Orifice method provided afflux of 0.81 and 1.03 m for 20 and 12 m clear span, respectively.

Keywords

Snowmelt and Rainfall intensity; Time of concentration; Rational method; HFL; Slope-Area method; Flood frequency; Return period

Introduction

The hydrologic and hydraulic studies are required to evaluate the performance of the existing cross-drainage structures (bridges and culverts) or to propose new one across the roads and highways. Design floods (HFL and Discharge) of specified return periods (25 years for the culverts, 50 years for the minor bridges and 100 years for the major bridges having span of more than 60 m) are the basic components and required to be computed using structural, survey, meteorological, DEM and stream data, topographical map studies, catchment's characteristics and various computational techniques [1] depending upon available regional/country codes. Further other hydraulic features of the bridges i.e. effective linear waterway, clear span, HFL, afflux, velocity and scour depth are computed using the design discharge and codes [1,2] or as per provisions of concerned territory. Although flood estimation reports or guidelines [1-3] do not cover snowmelt augmented flood part but it is essential for designing bridges/culverts in snow and glacier dominating catchments, especially under varying climatic conditions.

A rain-on-snow caused flooding damaged homes, utilities, sewer services, roads, numerous bridges and culverts, i.e. in May 7 1965 at Natrona, Converse, Albany, Platte, Denver; in 7 May 1973 at Jefferson, Denver, Arapahoe, Kiowa, Golden, Denver, Englewood; in 15 May 1978 at Park, Big Horn, Sheridan, Campbell, Crook, Weston, Johnson, Washakie, Hot Springs, Natrona, Converse; in 6-7 May 1988 at Park, Big Horn, Washakie [4]. The most damaging floods in rivers of the Sierra Nevada of California have occurred during warm storms when during April-July rain fell in snow covered catchments as in 1996; California has historical events in past 1913, 1925, 1939 etc. [5]. Forensic engineering investigation into the flood conditions of 2009 experienced by damaged and collapsed highway bridges in Cumbria, north-west England [6] and highlighted the importance of an effective bridge hydrology design and management.

It has been observed that uncertainty of risk of natural hazards assessment increases due to presence of flood at the bridge site, hence combined effect of earthquake and flood-induced scour on a highway bridge located in a seismically-active flood-prone region of California has been assessed for the design and safety measure [7,8]. The Rail cum Road Bridge having well foundations on the river Ganga at Munger [9] during design flood has relatively less volume of snow and glacier melt, but it has significant impact. Climatic warming may delay the timing and enhance the peak by 150% and 170% of initial flow at around 2050 and 2070 in the west and east Himalaya, before declining until the respective 63 glaciers disappear in 2086 and 2109, respectively [10,11] which are unrealistic and hypothetically exaggerated [12]. Climate warming will most likely shift precipitation from snowfall to rainfall with earlier snowmelt, resulting in much earlier runoff than historic conditions. Heavy rainfall in late June 2013 augmented by rapidly melting alpine snow by 30% triggered highest flood of 60 years return period throughout southern half of Alberta, matching historical flood of late 1800s and early 1900s, damaging roads, residents, bridges and culvert [13], The Ésera river in the Pyrenees, Northern Spain caused widespread damage during 18-19 June 2013 due to flooding as a result of torrential rains augmented by 33% snowmelt of total runoff [14].

In the snowmelt and rainfall models, the false positive peaks appear during long and intensive snowmelt events [15]. Consequently, instead of depending on conventional watershed models having snowmelt option ornamentally, an independent estimation of snowmelt contribution in generating the augmented deign flood is an important issue which has been resolved through this present study.

Materials and Methods

Study region

Two bridges of clear span between 10 and 20 m for highways in snowy catchments have been considered to assess their design discharge, hydrological and hydraulic features. The study bridges, Wagund bridge (no. 219/1) of 16 m span and Pernigaon bridge (no.

***Corresponding author:** Anand Verdhen, M.Tech, Ph.D and Alumni, Civil Engineering Department, Indian Institute of Technology, New Delhi, India, Tel: 9911960776; E-mail: anand_indra3@yahoo.co.in

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221/1) of 14 m span belong to Jammu-Srinagar road (NH1A). Figure 1 shows the study area and location of the bridges. Salient features relating the existing bridges are given in Table 1. The 24 hourly rainfall in the region extracted [3] for 50 years RP (return period) is 180 mm (18 cm). The entire catchment receives snowfall from late December to late April month [16].

The maximum snowpack generally builds up by the month of February. Snowmelt contribution to the flow becomes significant here from the month of March.

Rainfall and snowfall data

For finding the design discharge of any desired return period (50/100 years for bridges) rainfall intensity of that design return period has been determined for the concerned drainage basin. In India, on account of missing rain-gauge stations in the basin or nearby, 24 hours rainfall of design return period is obtained from the isohyets plotted for that in the Flood Estimation Report [3] pertaining to Hydrological zone/sub-zone-7, published jointly by CWC (Central Water Commission), IMD (Indian Meteorological Department), and MoR&ST (Ministry of Road and Surface Transport) [3]. Rainfall of 180 mm corresponding to 50 year return period has been obtained from Hydrological Zone-7 [3]. This 24-hourly rainfall has been attuned further for evaluating design storm corresponding to the time of concentration (t_c) of the study catchments. Snowfall and snow cover data are being collected for the project duration only or being obtained from the Snow and Avalanche Study Establishment (SASE) for unclassified observational network. In absence of ground truth observation, satellite data, literature and grid (of km 0.5 × 0.5 or 1 × 1) averaged precipitation and temperature data from e-resources are helpful.

Snowmelt intensity and contribution

The melting period starts in late February and March at the study locations/catchments, located between 1780 m and 3000 m altitude. By the month of May snow cover gets melted away. There is no glacier in the catchment to further contribute the melt-flow. Melting is peak during after noon. If there is a rain of 50 years return period during the peak melt in the month of April/May the runoff gets added to yield design discharge. The contributing area factor (*f*) may vary from 0 to 1. Hence, five cases have been envisaged and probable contributing area shown in Table 2.

The snowmelt intensity (M_i)=1.25 cm°C^{-1}d^{-1} on average (degree-day observed). Eighty per cent of daily melt occurs in six hours. Hence, effective snowmelt intensity comes 0.21 cm°C^{-1}hr^{-1}. The M_i can be obtained by temperature of the day, the maximum temperature for peak melt and the mean air temperature for the daily average melt. Average melt rate has been determined corresponding the 15°C temperature during May at the study area (M_i=0.21 × 15.0=3.15 cm/h).

Concentration time and rain intensity

Time of concentration (t_c) was determined on the basis of stream lengths (L), shape of the catchment, land use and drainage pattern.

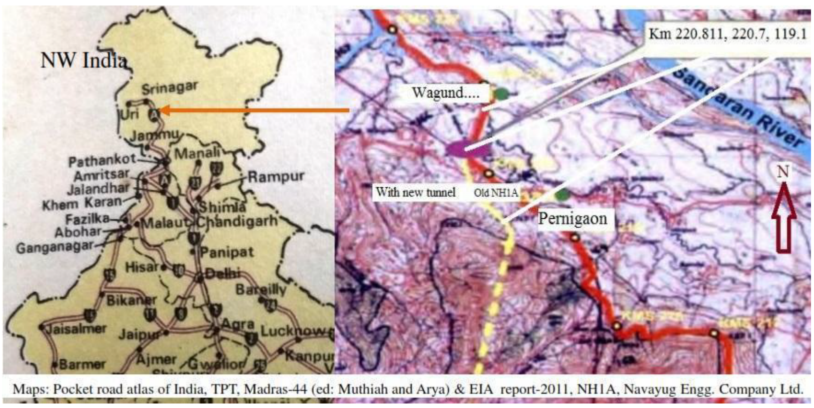

Figure 1: Study area and location of the bridges.

Table 1: Salient terrain and structure features of study bridges.

Stream/Bridge name		Wagund	Pernigaon	Near Kajikund
Features	Units	Site 1	Site 2	Remarks
Stretch	km	220.29	218.293	Old Chainage of the road
Bridge	no.	221/1	219/1	Bridge reference no.
Span	m	15.8	14	Existing span arrangement
Bed RL	m	1737.64	1801.724	Invert reduced level (RL)
Deck RL	m	1744.68		Existing deck top level above sea level
C_A	km^2	22	2.81	Catchment area (C_A)
L_c	km	12	6.35	Channel length with torchiticity (Lc)
B	km	3.32	0.84	Basin averaged width (B)
L	km	6.63	3.35	Basin averaged length (L)
S	v/h	0.00461	0.067	Longitudinal slope of the R. bed at bridge
H	m	1056	1200	Elevation drop top to outlet of the stream
R24	cm	18	18	24 h rain of 50 y RP (Zone-7 [3])

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The t_c has been found by both methods, empirical and time of travel from farthest point of the catchment:

Empirical method:

$$t_c=[0.87(L^3/H)]^{0.385} \quad (1)$$

Where L is the length of catchment [km]; and H is the elevation difference [m]. The L and H measurements are given in Table 1.

Time of travel:

$$t_c=(L_c/V_c)+(B/(2*V_B)) \quad (2)$$

where L_c=main channel length [km]; V_c=mean velocity of flow along the main channel [1.75 m/s]; B=average width of catchment contributing flow to the main channel and V_B=mean velocity of the lateral contributing flow [1.0 m/s]. It is better to have an average t_c of Equation (1) and (2) for finding design rainfall intensity (I_c) from daily rainfall value of 18cm in the region.

$$I_c=(F/t) \times ((t+1)/(t_c+1)) \quad (3)$$

I_c=design rainfall intensity [cm/hr]; F=24 h rainfall of 50 years return period [cm]; t=duration of F rain [hr]; t_c=average concentration time.

Lc and B measurements are given in Table 1, while the computed t_c and I_c values are given in Table 3.The point rainfall intensity (I_c) has been adjusted for an aerial mean value using envisaged, and recommended spread factor (*f*) as per IRC code [1], Table 2 and CWC report [3].

Methodology of design discharge

Methods adopted in any particular case depends on site conditions and data available [17].

Discharge analysis used are based upon catchment characteristics, cross-sections and long-section information and Weir/Orifice approaches as elaborated in guidelines [1] and report [3]. Having annual peak discharge data not available, statistical package suitable for comparison [18] or Gumbel distribution, sufficient for frequency analysis, could not be used in this study.

Catchment based methods: Empirical method (Dicken's formula), rational method, synthetic unit hydrograph, watershed models are used for computation of flood discharge based on runoff coefficient (C_r/C_d), catchment characteristics and rainfall intensity. First two methods, Empirical and rational have been used for computation of discharge.

River geometry based method: Slope- Area method based on Manning's equation has been used. Observed HFL (Highest Flood Level), longitudinal profile of the deepest river bed and various cross-sections at u/s and d/s of the bridge site, normal to the longitudinal profile, and identified rugosity coefficients have been used.

Statistical method: Several methods of extreme value distributions are generally used, e.g. Log–normal, Log-Pearson, Gumbel's distributions, etc. For carrying out frequency analysis, observed annual flood peak discharge/levels at the site of interest is required at least for 30 years. No such flood records are available for the study sites.

Existing structure based method: Sample, Weir/Orifice formula has been modified and applied to estimate discharge for the available HFL and bridge span or vice-versa.

Catchment based formula: Empirical formula has been used for computation of flood discharge.

Dicken's formula: $Q_e=C_d \times C_A^{0.75}$ (4)

Where Q_e=empirical discharge [m³/sec]; C_A=catchment area [km²]; and C_d=runoff coefficient which depends on the terrain and climate. For the study region C_d=14 has been determined on observed discharge of nearby catchments. To take care of snowmelt influence, Cd is revised by multiplying with a factor, $(M_i+I_c)/I_c$. The C_A is given in Table 1, while the values of M_i, C_d, C_r and computed Q_e are given in Table 3.

Rational formula: $Q_r=0.028\, Cr\, f_i\, C_A\, I_c$ (5)

where Q_r is discharge of 50 Yrs return period [m³/sec]; C_A=catchment area [ha]; I_c=critical intensity of rainfall [cm/h]; C_r=runoff coefficient=0.7; f_i=spread factor for converting point rainfall/melt into an aerial mean rainfall/melt; f_i=the spread factor as per Table 2, defining as f_0=0, f_1=0.98/1, f_2=0.4, f_3=0.3 for probable rainfall and melt intensity combination under case I, II, III, IV and V. The rational method has been modified in this light to take an account of snowmelt and rainfall to yield an average discharge (Q_{ra}).

Q_{ra}=Average {Case I: [$Q_{rI}=0.028\ C_r\ C_A\ (f_1\ I_{c+}f_0\ Mi)$]; Case II: [$Q_{rII}=0.028\ C_r\ C_A\ (f_2\ I_c+M_i)$]; Case III: [$Q_{rIII}=0.028\ C_r\ C_A f_3\ (2I_c+2M_i)$]; Case IV: [$Q_{rIV}=0.028\ C_r\ C_A\ (f_0\ I_c+\ f_1 M_i)$]; Case V: [$Q_{rV}=0.028\ C_r\ C_A\ f_1(I_c+M_i)$]};

$$Q_{ra}=(Q_{rI}+Q_{rII}+Q_{rIII}+Q_{rIV}+Q_{rV})/5 \quad (6)$$

The computed discharge Q_{rI}, Q_{rII}, Q_{rIII}, Q_{rIV}, Q_{rv} and Q_{ra} are given in Table 3.

Slope- area method:

Method is based on conveyance factor (K) and the slope (S) of stream. For calculation of the conveyance factor, three cross-sections (at bridge site, 30 m upstream and 10/20 m downstream of the bridge site depending upon the span and clarity of the section) have been used. The discharge (Q_{sa}) has been calculated using Manning's formula, given below:

$$Q_{sa}=K_e\, S_{1/2} \quad (7)$$

$$K_e=\text{Mean conveyance rate}=(K_1, K_2 \ldots K_n)^{1/n} \quad (7a)$$

$$K_n=(1/N_n)\, A_n\, R_n^{2/3} \qquad (n=1, 2, 3\ldots n) \quad (7b)$$

A=cross-sectional area of flow [m²]; R=hydraulic mean depth, Area/Perimeter [1.9 m and 0.79 m for stream 1 and 2, respectively];

Table 2: Contributing catchment area factor (*f*) for the probable rain, melt or both.

Case	Probable condition	Area factor (Site 1)	Area factor (Site 2)
Case I	For rainfall only	0.98	1
Case II	For rain and for melt	0.4 for each of two	0.4 for each of two
Case III	For rain, rain+melt, and melt	0.3 for each of three	0.3 for each of three
Case IV	Only snowmelt contributes	0. 98	1
Case V	Rain+melt contribute together	0.9	0.9

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N=rugosity coefficient [0.035 to 0.045]; S=mean longitudinal slope of the channel (Table 1); K=conveyance factor; and n refers no. of cross-section; Conveyance factor (K_n) for each (1 to n, n=3) cross-sections has been determined to have an equivalent Ke and discharge for HFL (Highest Flood Level) or vice-versa, using Equation (7). The natural width of channel W_c, N values, computed discharge Q_{sa} and corresponding normal HFL values are given in Table 3.

Results and Discussion

The result of different methods may vary due to data used or suitability of the particular method and experience of the designer. Results based on conceptual and systematic analysis may not vary much. The results of peak discharge computation using empirical method (Qe, Eqn. 4), modified rational method (Q_{rI} to $_{rV}$, Eqn. 6) and slope area method (Q_{sa}, Eqs. 7) are listed in Table 3 for both the bridges. The rivers are perennial in nature and base flow (Qb) in tune of 4% has been added to compute design discharge. The maximum value out of the methods adopted, ignoring the outlier, is considered for peak discharge as per the codal provision of rainfall-Runoff [1]. Here five probable options for the rain and snowmelt combination have been tried and the fifth options with rain and melt simultaneously (Q_{rv}) yield maximum value, which may be possible for the small catchment. However, other 2nd to 4th options show relatively low value. Consequently, an criterion i.e. out of the average of all the five options (Q_{ra}) or the modified average with first and fifth options (Q_{ra}), neglecting 2nd to 4th options of rational method or the discharge computed by empirical (Q_e) and slope-area method (Q_{sa}), which ever found higher has been found suitable for the peak design discharge ($Qd50_{yr}RP$, Table 3), which are 395 and 71 cumecs for the Wagund and Pernigaon bridges, respectively.

Slope-area method helps in computing discharge as well as the Highest Flood Level (natural HFL) without obstruction in channel, valid for the uniform flow. The rugosity coefficient of 0.035 to 0.045 has been considered as per site condition. Natural condition HFL of 50 years period has also been calculated using design discharge ($Qd50_{yr}RP$, Table 3), which may be supposed to be the level equivalent to the d/s of bridge site. The size of clear opening (O_d), HFL_d and afflux (heading, h) determined based on the design discharge using weir and orifice methods are listed in Table 3.

The clear span size, discharge and afflux trials converge for the Wagund bridge by weir method while for the Pernigaon bridge these converge by orifice method satisfying the conditions ($h/D_d<0.25$ for weir and ≥ 0.25 for orifice; where D_d is d/s flow depth and afflux, h is the difference of u/s flow depth minus d/s flow depth, i.e. HFL_d - Normal HFL). The bridges clear span (O_d) with 20 m and 12 m has been constrained at 0.8 from channel natural width (W_c) 35 m and 15 m resulting in afflux of 0.81m and 1.03 m, respectively. While in alluvial plain afflux is expected up to 0.15 m in order to mitigate upstream submergence and pier scour. However, gorge section, steeper slope, rocky base of channel in mountainous region such afflux up to 1.0 m may be permitted. In bridge hydraulic design seismic condition is not in the scope of present study, but it should be considered also [7,8] for an additional safety of structure.

The rainfall and snowmelt intensity induced flow in small time of concentration yields peak discharge, irrespective of reduced runoff coefficient from 0.85 to only 0.7 due to snow cover.

Hence, snowmelt impact is critical for the safety of structures in the mountainous region.

Consequently, rational method with an average of discharge with exclusive rain and rain plus snowmelt is suitable criteria for small catchment to have design discharge in snow receiving mountainous area and as such regions.

Heavy rainfall and rapid snowmelt or cloud bursts including glacial lake outbursts etc. are the prime reasons of floods in high

Table 3: Salient hydrologic and hydraulic features of the study bridges.

Features	Units	Site 1	Site 2	Remarks
Stream/Br	Name	Wagund	Pernigaon	Near Kajikund
tc	hr	1.445	0.67	Average time of concentration (Eqn. 1-2)
Ic	cm/hr	7.67	11.21	Rainfall intensity at 50 year Return Period (Eqn. 3)
M_i	cm/hr	3.13	3.13	Melt intensity (at 15°C, spatio-temporal varying temp)
C_d	-	20	18	Coefficient for Empirical (14 for rain to rain+melt)
Q_e	m^3s^{-1}	200	39	Empirically computed flood discharge (Eqn. 4)
Cr	-	0.7	0.7	Runoff coefficient for Rational method
QrI	m^3s^{-1}	321.7	61.3	Rational Q (I: only rainfall; f=0.98|1.0) (Eqn. 5)
QrII	m^3s^{-1}	184.8	31.3	Rational Q (II: rain, f=0.4; melt, f=0.4) (Eqn. 6)
QrIII	m^3s^{-1}	277.3	47	Rational Q (III: rain; rain+melt; melt, f=0.3 each)
QrIV	m^3s^{-1}	127.1	16.2	Rational Q (IV: only snowmelt; f=0.98|1.0 each)
QrV	m^3s^{-1}	439	74.4	Rational Q (V: rain+melt both, f=0.9 each) (Eqn. 6)
Qra	m^3s^{-1}	270	46	Rational Qra (average of all cases, case I to case V)
Qram	m^3s^{-1}	380.4	67.9	Rational Qram (average of case I and case V only)
N	-	0.035	0.045	Manning Rugisity coefficient
Qsa	m^3s^{-1}	325	79	Slope- area method discharge (Eqn. 7)
Q_b	m^3s^{-1}	15	3	Base flow for perennial stream (@4%)
Qd50RP	m^3s^{-1}	395	71	Design discharge at 50 y RP
W_c	m	35	15	Channel natural width
HFL	m	1741.92	1803.346	Normal HFL at 50 y Return Period
Span (O_d)	m	20	12	Proposed clear span
QW/O	m^3s^{-1}	395	71	Qd forWeir/Orifice based design HFL
Heading, h	m	0.81	1.03	Heading, afflux due to fluming
HFLd	m	1742.73	1804.376	Design HFL at 50 y return period

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mountainous regions [19]. The climate change issue is very important to flooding. Kundzewicz et al. [20] assessed the literature included in the IPCC SREX report and new literature published for the changes in flood risk in seven of the regions considered in IPCC SREX report—Africa, Asia, Central and South America, Europe, North America, Oceania and Polar regions and concluded having low confidence on the inference about projected increase based on climate models. However, they encouraged the continuation of empirical and model-based science and a "no regrets" strategy for limiting flood losses. To explore the climate change issue on magnitude and frequency of flood occurrence in Sweden, Arheimer and Lindstrom [21] observed time series of past century throughout the country. Temperature was found to be the strongest climate driver of changes in river high flows, which are related primarily to snowmelt in Sweden. The current boundary between snow-driven floods in northern–central Sweden and rain-driven floods in the south may move toward higher latitudes due to less snow accumulation in the south and at low altitudes, which is also valid for the study region.

Conclusion

Hydrological analysis in absence of adequate hydrological data and suitable code of practice for design precipitation intensity in the form of rain and snowmelt in snow bound region and the decision on design discharge become subjective. Uncertainties increase if existing structure does not work efficiently due to climate change impact or otherwise. The methodology developed and applied for two bridges indicate that the consideration of various good and worst scenario help in achieving satisfactory result for small catchment area/t_c. It removes the possibility of over or under estimation of either design peak discharge or design HFL.

HFL_d for Highways bridges, under estimation damages upstream, aggravates erosion, creates overtopping situation and even leads to the failure of structure. Whereas, over estimation increases the investment without reason. Therefore, it is essential to give especial emphasis on designing the input parameters for the hydraulic structures and requires developing a comprehensive guidelines/code of practice for that. This paper may provide an outline in that direction.

Study reveals that rational method with an average of discharge with exclusive rain and rain plus snowmelt is suitable criteria for small catchment to have design discharge in snow receiving mountainous area and such regions. Design discharge of 395 and 71 cumecs for the Wagund and Pernigaon bridges, respectively were found. Using this design discharge, determination of normal HFL by Slope-area method and fixation of clear span of the bridges and afflux by the weir-orifice method is usually good proposition. The bridges clear span with 20 m and 12 m has been constrained at 0.6 and 0.8 from channel natural width of 35 m and 15 m resulting in afflux of 0.81 m and 1.03 m, respectively. The prolonged climate warming, resulting in increased rainfall, early snowmelt or catchment free from snow cover, the impact of snowmelt becomes insignificant and design discharge depends exclusively on effective designed rainfall. Under such situation, instead of 50 years return period, design discharge of 100 years return period can be considered including seismic study for an additional safety of structure.

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Author Affiliations

Top

Civil Engineering Department, Indian Institute of Technology, New Delhi, India