PERFORMANCE OF SKEW INTEGRAL BRIDGE UNDER DYNAMIC LOADING

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Abstract— In this study, the integral and simply supported bridge with total length of 200 m non-skew and skews were designed, and modeled in SAP2000 software and analyzed the results in terms of moments, shears and stresses under static and dynamic loading were considered and checked with allowable stress method. Extreme stresses that exceed allowable limit in the superstructure and substructure of integral bridges were reduced by using six different stress reduction methods. The integral bridge analysis results were compared with that of simply support bridge result to analyze skew effect and integral effect. The propose of this study was to analyze behaviour of integral, skew angle, and to reduce extreme stress of integral bridge under dynamic loading. The parameters investigated in this analytical study were bridge support type, skew angle and stress reduction methods. The geometric dimensions of the Integral Bridge and the loading used were in compliance with AASHTO standard specifications. Static analysis and dynamic analysis of moving load analysis and nonlinear time history analysis were performed to assess the seismic performance of integral bridge. The FEA results indicate that under static live load, integral bridge girder shear force was minimum in skew 60°, but maximum moment that was opposite to simply supported bridge girder. Under dynamic moving load analysis, integral abutment bored pile moment and shear force were maximum in skew 60°, but maximum in skew 15° for integral pier bored pile. Under dynamic seismic time history analysis, maximum bending and shear stress occurred at integral abutment foundation and integral pier foundation in non-skew (0°) and minimum skew angle 15° bridge, Among six stress reduction method, MSE wall and HLAC method can reduce stress within allowable limit for non-skew and skewed bridge over 90% and 23% respectively. According to analysis result, MSE wall is the best stress reduction method in skew and non-skew integral bridge.

Keywords— Integral, bridge, skew, stress, static, dynamic, moving load, reduction, steel plate girders, integral abutment, and integral pier

I. INTRODUCTION

Integral abutment bridges (IABs) have been used for decades in the United States. Their use reduces both construction and maintenance costs and remains in service for longer periods of time than conventional bridges with only moderate maintenance and occasional repairs. In addition, they exhibit good earthquake resistance. Integral abutment bridges can be described as bridges generally built with their superstructures integral with the abutments, and avoid expansion joints and movement bearings for the entire length of the superstructure.

The skew angle can be defined as the angle between the normal to the centerline of the bridge and the centerline of the abutment or pier cap. Since skewed bridges tend to rotate during a seismic event, which can cause excessive transverse movement. Because relatively limited research has been conducted on integral abutment bridges this paper presents an analytical procedure for nonlinear time history analysis of non-skewed and skewed integral bridges subjected to near-field ground motions.

II. MODELING INTEGRAL BRIDGE

In this study, the 5 number of 40 m span four lane concrete slabs on nine steel plate girders with integral abutment and integral pier were considered. Bridge with different skew angle of 15 degree, 30 degree, 45 degree and 60 degree were modeled and analyzed under static and dynamic loading.

The bridge, which was located on Kalay Township, near Chindwin River, carries four lanes traffic over HS20-44. The road way width was 16 m, integral abutment width is 1.5 m and 10 m high, the steel plate girder height is 2m resting on integral abutment directly and at intermediate piers rest on cross beams resting on 1.5 m diameter multi-column integral pier with height of 10 meter. The deck and steel plate girders are continuous and monolithic with abutment wall and piers bear on a row of nine 1.5 m diameter piles foundation.

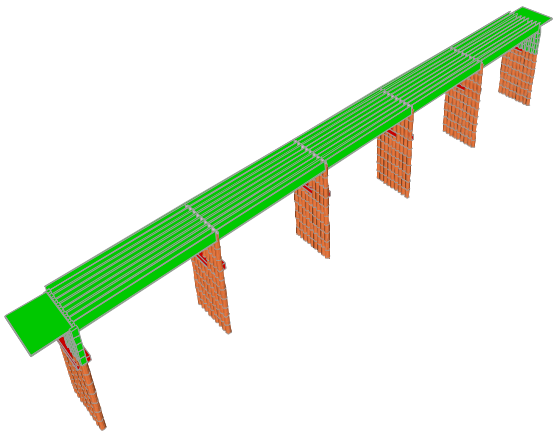

Fig. 1 Modeling of Integral Bridge.

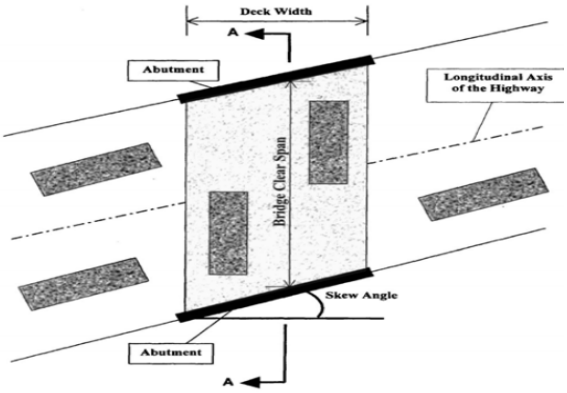

Fig. 2 Description of Skew Angle

III. DESIGN CRITERIA

Neither the AASHTO-LRFD Specifications nor the AASHTO-Standard Specifications contain detailed design criteria for integral abutments. In the absence of universally accepted design criteria, many states have developed their own design guidelines. These guidelines have evolved over time and rely heavily on past experience with integral abutments at a specific area. Criteria for integral abutments is such that maximum Span Length for Steel Bridge is 40m, total Bridge Length is 200m, and Skew angle is 45°. Department of Transportation in Colorado limit the maximum bridge length was 195m for steel bridge, 240m for concrete. Tennessee limit that 152 m for steel bridge, 244 m for concrete. Ontario, Canada limit that 100 m for steel and concrete bridge. Washington limit that 91 m for steel bridge, 107 m for concrete. Illinois limit that 95 m for steel bridge, 125 m for concrete. It is noteworthy that concrete bridge are more recommended than steel bridge as integral structure.

IV. MATERIAL SPECIFICATION

The table show material specification used for concrete member in the analysis. Firstly, normal weight concrete was used in the analysis without stress reduction method. High performance concretes and high performance lightweight concretes were used as stress reduction method mention in article VI. C and D.

TABLE I
MATERIAL SPECIFICATION

	Normal Weight Concrete NWC	High Performance Concrete HPC	High Performance Lightweight Concrete HLAC
Modulus , E (PSI)	3604997	4029888	2692080
Poisson ratio, v	0.2	0.2	0.2
Unit weight , r (lb/ft3)	145	150	110
Compressive / Tensile strength , Fc' (ksi)	4	10	5
Allowable concrete bending stress, Fca (Psi) = 0.25 Fc	1080	4060	2030
Allowable concrete bending stress, Fca (Psi) = 0.25 Fc'	1080	4060	2030
Allowable concrete shear stress, Fsa (Psi) = 0.05 Fc'	240	609	305

IV. ANALYSIS PROCEDURE

In this study, the integral and simply supported bridge with total length of 200 m non-skew and skews were design and modeled in SAP2000. Then, applied loading such as dead load, changes in temperature, wind load, breaking load, high speed moving load, and seismic load in additional to gravity loads, earth pressure and surcharge load. Firstly, static analysis were performed using 61 mph speed moving load in integral and simply supported bridge with non-skew and skewed angle to study effect of integral and simply support bridge moment and shear in steel girder, then check the structure stability and stress.

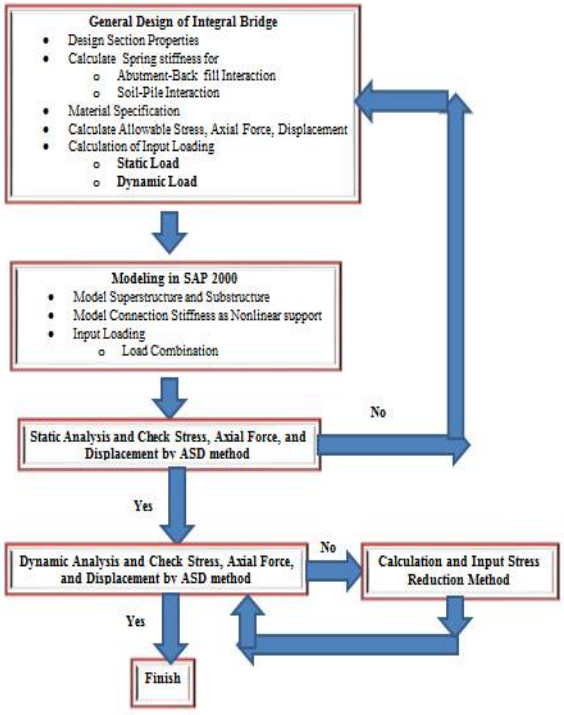

Fig. 3 Analytic Procedure.

After the bridge structure is stable, 112 mph high speed moving dynamic load analysis were performed in integral bridge with non-skew and skew angle to check stress to satisfy within allowable limit. Then, seismic load nonlinear time history analyses were performed in integral bridge with non-skew and skew angle to assess the seismic performance of integral bridge and to check stress to satisfy within allowable limit. From the analysis result due to extreme dynamic loading, the stress that exceeds allowable limits had to

be reduced to obtain within allowable limit. Therefore, six different stress reduction methods were considered in the analysis and reanalysis again. The purpose of this analysis was to study performance of skew integral bridge and to find best stress reduction method under dynamic loading.

V. STRESS REDUCTION METHOD

In the analysis, to reduce stress, moment and shear in integral bridge component, six different stress reduction methods were used.

A. Mechanically Stabilized Earth or MSE wall behind Abutment

Mechanically, stabilized earth or MSE is soil constructed with artificial reinforcing. Use of MSE walls with inextensible reinforcements was, and still is, performed by assuming the MSE structure behaves as a rigid body, to resist external loads applied by the retained soil and by any surcharge. MSE wall is used to reduce moment due to displacements in both lateral directions and to reduce bridge lateral displacement. The mechanically stabilized earth wall is located under bridge deck in front of the embankment.

In the analysis, square foundation width of MSE wall is 0.7 times height of integral abutment, taken as 10 m. Height of MSE wall is same as height of abutment. The soil reinforcement length used in MSE wall is same as MSE wall foundation width. Soil reinforcement spacing is 2 m apart which is less than allowable min spacing of 0.2 m. The MSE wall and soil reinforcement restraint integral abutment with facing plate in front of abutment. The MSE wall facing plate may be fiber or thin cement concrete slab with thickness of 0.02 meter. These MSE wall was modeled as spring stiffness applied to abutment in lateral direction, i.e., both transverse and longitudinal direction. The MSE wall spring stiffness were, calculated and applied as a portal frame structure.

$$Kmse = 2.5\, G(A^{0.5}) / (1-v)$$

Where, G is shear modulus of MSE reinforcement, v is poison ratio, A is the abutment area.

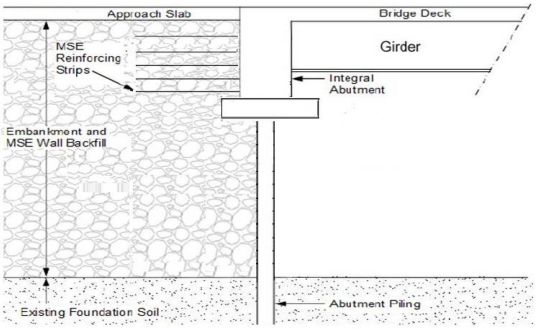

Fig. 4 Integral Abutment with MSE wall

B. Use of Sand Pile around Foundation Pile

Using sand Pile around foundation pile improve load bearing capacity and control settlement of piles. The stress displacement of footing rested on soft soil layer, significantly decrease the settlement. The displacement of foundation induces stress on integral abutment and pier. Therefore, the bearing capacity failure mechanism of footing rested on soft clay can be modified from exclusive settlement to general bearing capacity failure at the tip of confined replaced sand column. The bridge soil layer was upgraded by using 0.2 meter diameter sand pile is driven with spacing of 0.3 meter around foundation piles that produce sand layer. In the analysis, the sand layers around foundation piles were modelled as a spring model in axial and longitudinal direction. The spring stiffness values are calculated based on sand layer properties. Then, spring stiffness values are applied to pile foundation model.

Longitudinal spring stiffness, $K_H = K_{HO}\ (B_H/0.3)^{(-3/4)}$

Axial spring stiffness, $K_V = a\ A_p\ E_p/L$

Where, $K_{HO} = \alpha Eo/0.3$

C. Application of High Performance Light weight Aggregate Concrete, HLAC

In general, dead load is the major load in design of bridges; especially self-load of deck/girder often takes largest share in all the primary loads. Lightweight aggregate concrete is one of the most effective solutions to extend the application of integral bridges, if it can clear the durability and cost requirements. The lightweight aggregate concrete bridges have been rarely constructed in Japan because of its scant frozen-thawed resistance. High performance lightweight concrete (HLAC) means the concrete has higher frozen-thawed resistance than conventional concrete.

D. Application of High Performance Normal weight Concrete, HPC

High performance concrete has the main properties such as high strength, high workability, high durability, ease of placement, compaction without segregation, early age strength, long-term mechanical properties, permeability, density, and heat of hydration, toughness, volume stability, and long life in several environments.

E. Use of Extended Approach Slab in Front of Abutment

In general, Bridges with integral abutments were constructed in the past with and without approach slabs. Traffic and seasonal movements of the integral abutments cause the fill behind the abutment to shift and to self-compact. This often caused settlement of the pavement directly adjacent to the abutment then induced stress to abutment and foundation pile. In addition, the approach slab bridges cover the area where the fill behind the abutment settles due to traffic compaction and movements of the abutment. It also prevents undermining of the abutments due to drainage at the bridge ends. In the analysis, 10 m length and 16 m width extended approach deck slab

with 0.2 m thickness was provided at both end of the bridge deck slab without expansion joint.

F. Use of Elasticized Expanded Polystyrene EPS closing around Abutment or Pier

Expanded Polystyrene, EPS, geofoam is a super–light weight, closed cell, rigid, plastic foam. Geofoam has now been successfully utilized in a number of countries all over the world. Integral abutment issue of special interest is the effect of EPS material. This was investigated by analysing a case with elasticized EPS, horizontal moment and stress on the abutment and pier is about nine times smaller. Use of EPS geofoam has the advantages such as to provide restraint against progressive and excessive displacement of bridge, to distribute movements to both abutments and thereby reduce maximum stress, forces, and moments, to reduce maximum earth pressure behind abutment, to reduce shear loads in dowels. In the analysis, EPS geofoam is used as a cover sheet to the abutment wall, the pier shaft and cap. The thickness of EPS is calculated as per specification. The EPS thickness used in this analysis is 0.3 meter. The unit weight of EPS is 2.85 lb/cuft. The mass per unit volume of EPS is calculated and this value was applied to abutment wall, pier shaft and caps as a from mass properties in SAP 2000.

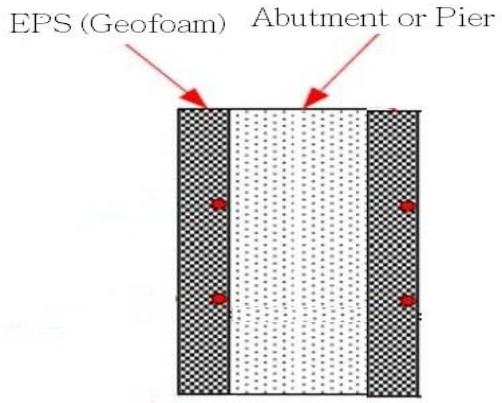

Fig. 5 Expanded Polystyrene EPS geofoam around Integral Abutment and Pier

VI. ANALYSIS RESULT

The proposed integral and simply supported bridge models with and without skew angles were analyzed under static, dynamic moving load analysis and seismic nonlinear time history analysis. The resultant moment and shear force and stresses at bridge components were checked whether bending and shear stress with allowable limits.

Under static analysis as shown in Fig 6 to Fig 9, in simply supported bridge all girders shear forces and moments were not changed at skew angle increase. In integral bridges, all girder shear forces decrease only in 60° skew angle, but moments increase in 60° skew angle.

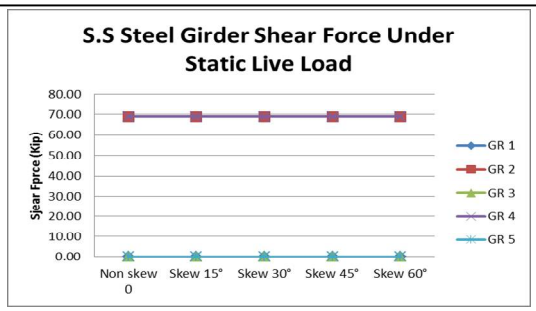

Fig. 6 Simply Supported Bridge Steel Girder Shear Force under Static Live Load



Fig. 7 Simply Supported Bridge Steel Girder Moment under Static Live Load

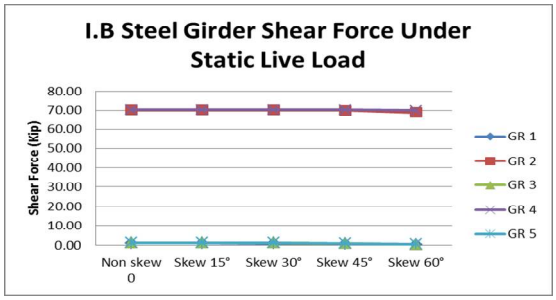

Fig. 8 Integral Bridge Steel Girder Shear Force under Static Live Load

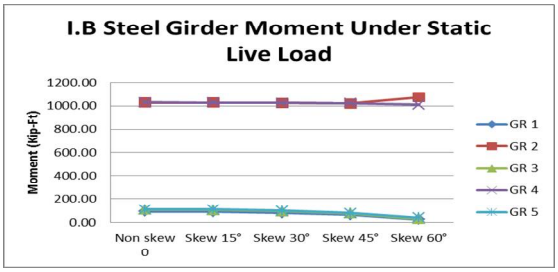

Fig. 9 Integral Bridge Steel Girder Moment under Static Live Load

Under static live load analysis, shear and bending stress at all components were within allowable limit. As shown in Fig 10 and Fig11, steel girder shears and moments remain no change in skew angle increase. Shear in abutment, abutment cap and abutment bored pile were not changed in all skews and non-skew, except minimum in skew 60°. Pier shaft, pier cap, pier cross beam and pier bored pile shear force increase in skew angle increase. Moment in pier shaft, cap and cross beam increase in skew angle increase. Moments and shear force were minimum in abutment bored pile and pier bored pile at skew 60°.

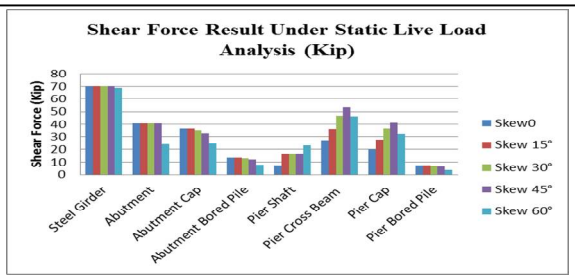

Fig. 10 Shear Force Result in Static Analysis

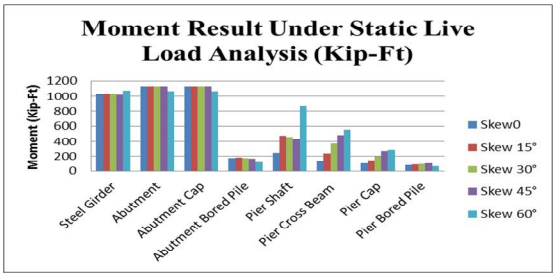

Fig. 11 Moment Result in Static Analysis

Under high speed dynamic moving load analysis, shear and bending stress at all components were within allowable limit and maximum in steel girder. From the analysis result as shown in Fig 12 and Fig 13, steel girder moments and shears were minimum in non-skew and maximum in all in skew angle with same value. Abutment moments and shears were minimum in skew 60°, maximum in other with same value. Cross frame member such that abutment cap, pier cap, pier cross beam shear and moment increase in skew angle.

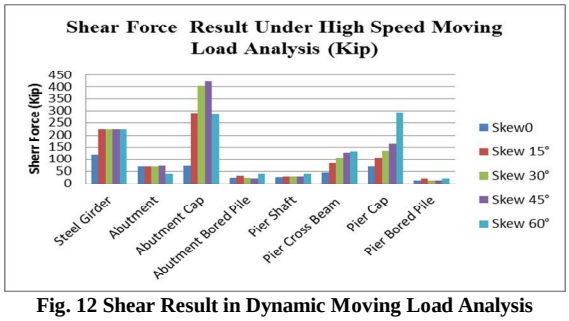

Fig. 12 Shear Result in Dynamic Moving Load Analysis

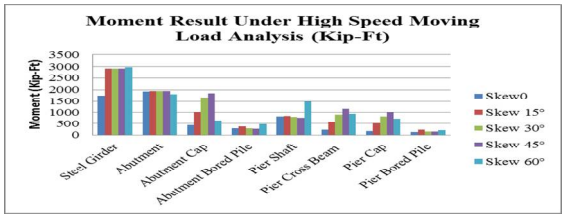

Fig. 13 Moment Result in Dynamic Moving Load Analysis

Under dynamic seismic time history analysis shown in Fig 14 and Fig 15, shear and moment were maximum at abutment cap and pier cap. Steel girder, abutment, abutment bored pile, pier shaft and pier bored pile shear and moment decrease in skew angle increase. Pier cap moment and shear increase in skew angle increase.

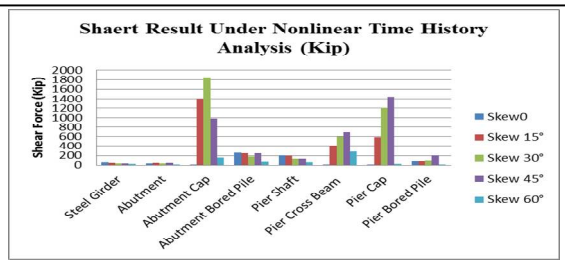

Fig. 14 Shear Result in Seismic Time History Analysis

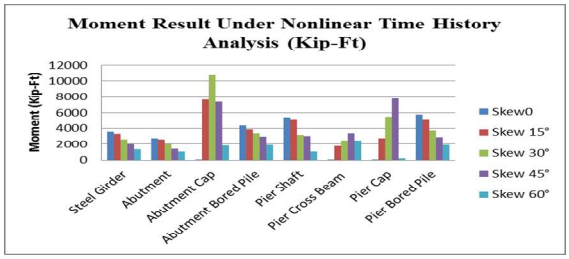

Fig. 15 Moment Result in Seismic Time History Analysis

As shown in TABLE II, under dynamic seismic time history analysis shear and bending stress were not satisfied within allowable limit at abutment bored pile and pier bored pile in non-skew and skew 15°, 30°. The comparison of analysis result of abutment bored pile and pier bored pile under dynamic moving and seismic time history analyses were shown in TABLE III to VI. In abutment bored pile and pier bored pile, bending stress are maximum in non-skew and 15° skew, and min in skew max of 60°. Therefore, reanalyze using six different stress reduction methods to reduce excessive stress.

TABLE II
CHECKING STRESS RESULT WITH ALLOWABLE LIMIT UNDER DYNAMIC SEISMIC TIME HISTORY ANALYSIS

Case	Steel Plate Girder	Abutment	Abutment Cap	ABBP	Pier Shaft	Cross Beam	Pier Cap	Pier BP
Non-skew	O.K	O.K	O.K	N.G	O.K	O.K	O.K	N.G
Skew15°	O.K	O.K	O.K	N.G	O.K	O.K	O.K	N.G
Skew0°	O.K	O.K	O.K	N.G	O.K	O.K	O.K	N.G
Skew45°	O.K	O.K	O.K	O.K	O.K	O.K	O.K	O.K
Skew60°	O.K	O.K	O.K	O.K	O.K	O.K	O.K	O.K

TABLE III
DYNAMIC MOVING LOAD ANALYSIS RESULT FOR ABUTMENT BORED PILE IN NON-SKEWED AND SKEW BRIDGE

Case	V (K)	M (K-ft)	Reduce M %	Fb (Psi)	fb< Fca	fv (Psi)	fv<Fsa
Non skew	23	300	0	105	O.K	8	O.K
Skew 15°	32	370	-23	129	O.K	12	O.K
Skew 30°	23	284	5	99	O.K	8	O.K
Skew 45°	22	268	11	94	O.K	8	O.K
Skew 60°	40	483	-60	168	O.K	14	O.K

TABLE IV
DYNAMIC SEISMIC TIME HISTORY ANALYSIS RESULT FOR ABUTMENT BORED PILE IN NON SKEWED AND SKEW BRIDGE

Case	V (K)	M (K-ft)	Reduce M %	Fb (Psi)	fb< Fca	fv (Psi)	fv <Fsa
Non skew	258	4387	0	1534	N.G	94	O.K
Skew 15°	246	3886	11	1359	N.G	90	O.K
Skew 30°	174	3407	22	1191	N.G	63	O.K
Skew 45°	246	2942	33	1028	O.K	90	O.K
Skew 60°	67	1898	56	663	O.K	24	O.K

TABLE V
DYNAMIC MOVING LOAD ANALYSIS RESULT FOR PIER BORED PILE IN NON-SKEWED AND SKEW BRIDGE

Case	V (K)	M (K-ft)	Reduce M %	Fb (Psi)	fb<Fca	fv (Psi)	fv<Fsa
Non skew	13	142	0	50	O.K	5	O.K
Skew 15°	22	229	-61	80	O.K	8	O.K
Skew 30°	13	145	-2	51	O.K	5	O.K
Skew 45°	13	154	-8	54	O.K	5	O.K
Skew 60°	21	204	-44	71	O.K	8	O.K

TABLE VI
DYNAMIC SEISMIC TIME HISTORY ANALYSIS RESULT FOR PIER BORED PILE IN NON SKEWED AND SKEW BRIDGE

Case	V (K)	M (K-ft)	Reduce M %	Fb (Psi)	Fb <Fca	fv (Psi)	fv<Fsa
Non skew	89	5734	0	2005	N.G	33	O.K
Skew 15°	80	5085	11	1778	N.G	29	O.K
Skew 30°	97	3727	35	1303	N.G	35	O.K
Skew 45°	196	2852	50	997	O.K	72	O.K
Skew 60°	6	1904	67	666	O.K	2	O.K

Where Fb is bending stress, Fv is shear stress, V is shear force, M is bending moment

The analysis results for non-skew and 15° skew bridge using six different stress reduction methods were shown in Fig 16 to Fig 19 and TABLE VII and VIII. In non-skew bridge as shown in Fig 16 to Fig 17, MSE wall method can reduce bending stress about 90% in steel girder, abutment bored pile, pier shaft and pier bored pile, 35 % in abutment, above 54 % in abutment cap. Sand piling method can reduce stress at pier shaft above 10 % only, but increase stress at abutment bored pile and pier bored pile to excessive stress. Using HLAC concrete can reduce stress at all bridge component like 4 % in pier cap, around 10 % at abutment, abutment cap, shaft, cross beam and 16 % at steel girder, above 23 % at abutment bored pile and pier bored pile. Using HPC concrete can reduce stress 12 % at steel girder, 18 % at abutment bored pile, above 20 % in pier bored pile, but increase bending stresses at pier cap that exceed allowable limit. Construction of extended approach slab at the end of the abutment can reduce stress at abutment bored pile and pier bored pile only slightly. Use of EPS foam enclosing abutment and pier can reduce stress only slightly at abutment cap, pier cross beam and pier cap. In 15° skew bridge as shown in Fig 18 and Fig 19, similar stress reduction behaviour occur like non-skew bridge, but HPC method can reduce around15 % in steel girder, abutment bored pile, pier cross beam and pier bored pile. In conclusion, at non-skew bridge excessive stresses can be reduced to obtain within allowable limit by using MSE wall and HLAC method about 99% and 23 % respectively. In 15° skew angle bridge, excessive stresses can be reduced by using MSE wall, HLAC and HPC method about 99%, 23% and 17% respectively.

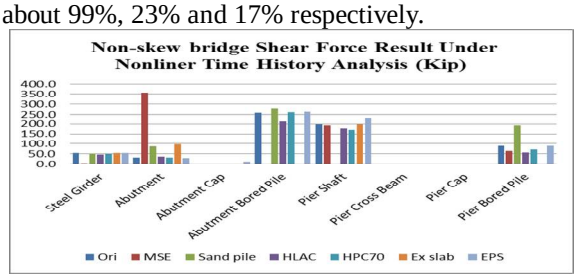

Fig. 16 Non-skew bridge Shear Force Result under Nonlinear Time History Analysis

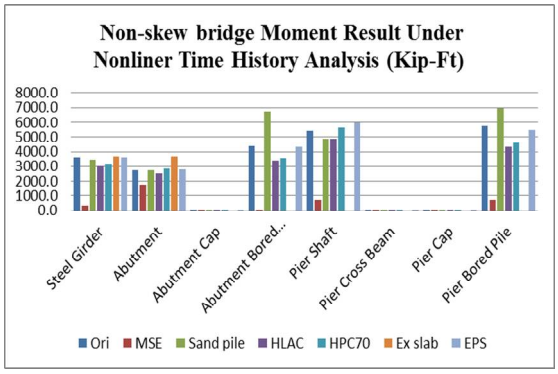

Fig. 17 Non-skew bridge Moment Result under Nonlinear Time History Analysis

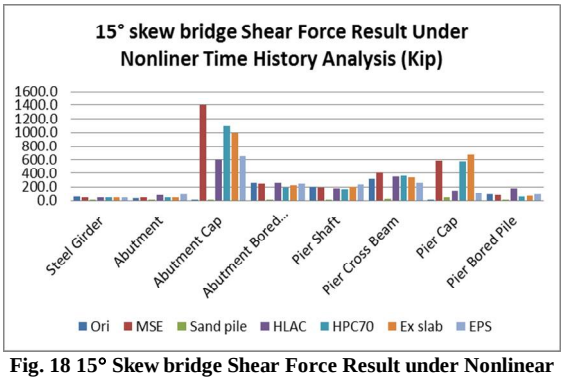

Fig. 18 15° Skew bridge Shear Force Result under Nonlinear Time History Analysis

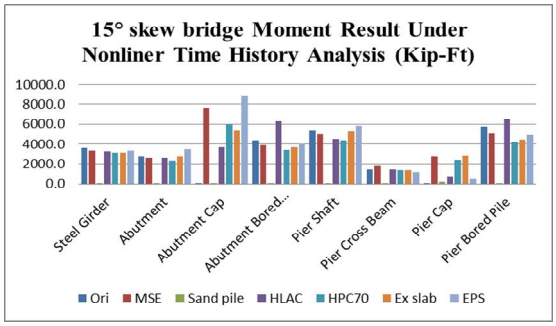

Fig. 19 15° Skew bridge Moment Result under Nonlinear Time History Analysis

TABLE VII
DYNAMIC ANALYSIS RESULT FOR NON SKEWED BRIDGE

Reduction Method	Stress Reduction % in Member	
	Abutment Bored Pile	Pier Bored Pile
Original Condition	N.G	N.G
MSE	99	257
HLAC	23	O.K

TABLE VIII
DYNAMIC ANALYSIS RESULT FOR 15° SKEWED BRIDGE

Reduction Method	Stress Reduction % in Member	
	Abutment Bored Pile	Pier Bored Pile
Original Condition	N.G	N.G
MSE	100	100
HLAC	23	27
HPC	17	23

CONCLUSION

Under static live load analysis, the opposite value occurs such that integral bridge steel girder moments were minimum in skew 60° but maximum in simply supported bridge. Shear and moment at cross frame member such as abutment cap, pier cross beam and pier cap increase in skew angle increase under high speed moving load analysis, but decrease under seismic load time history analysis. Abutment bored pile and pier bored pile shear and moment were small amount under moving load analysis, but increase about ten times under seismic time history analysis. Cross frame members such as abutment cap, pier cap and pier cross beam shear forces and moments were increased about ten times under time history analysis than moving load analysis except at non-skew bridge. In conclusion, integral bridge shear and moments were decreased in skew maximum that was disagreed in simply supported bridge. This shows that integral bridges were better seismic performance than simply supported bridge. Shear and moment in integral abutment decrease under time history analysis than moving load but at abutment and pier cap were much larger. This shows at earthquake time, integral bridge abutment distributes stress to cross frame member. Therefore, shear and moment behavior under moving load analysis and time history analysis were opposite integral bridges.

By using six different stress reduction methods, at all bridge components member's excessive stresses can be reduced within allowable limit by using only two method such as MSE wall and HLAC method in non-skew bridge. In 15° skew angle bridge, excessive stresses can be reduced by using three method such as MSE wall, HLAC and HPC method. For non-skew and skew bridge the best stress reduction method was using MSE wall behind abutment. The second most stress reduction method was using HLAC concrete in all concrete members.

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