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Effective Coefficient of Friction of Steel Bridge Bearings

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A study to determine experimentally the effective coefficient of friction of four classes of steel bridge bearings used by the Oklahoma Department of Transportation is reported. As-built, rusted, and in situ (debris at the moving surfaces) conditions were tested by using full-scale bearings under normal loads to 250 000 lb. In addition, the effects of manufacturing tolerances on bearing performance were analyzed. From the tests it was found that unturned pipe rollers exhibit the lowest effective coefficient of friction of the four rolling devices tested. For turned pipe rollers it was found that the equivalent coefficient of friction is a function of the amount of horizontal movement from the centerline. A geometric explanation was devised, and excellent agreement between predicted and measured results was achieved. Tests with a pintle rocker showed that fabrication inaccuracies, especially in the sole plate socket radius, can significantly affect the performance and effective coefficient of friction of the bearing. In all cases, tests with rusted bearing plates or with sand spread over the lower bearing plate showed significant increases in the effective coefficient of friction.

Expansion and contraction caused by temperature changes, deflection, relative support settlement, creep, and other factors will produce motion in a bridge. The movement is very slow, but the forces involved can be tremendous and usually are accommodated by bearings at piers or abutments. If the bridge does not have the ability to move, because either it does not have a bearing or the bearing is not working, it pushes and tears at its supports until it achieves the ability to move.

Even if the bearing is working properly, horizontal force is transmitted to the pier or abutment through friction caused by relative motion of the bearing parts or by eccentric loading of the bearing as found in certain "pipe" bearings. This force must be accommodated in the design of the supporting structure; if not, structural damage can occur.

The purpose of this study was to determine experimentally the effective coefficient of friction of several classes of bridge bearings used by the Oklahoma Department of Transportation (ODOT). Both as-built conditions and simulated conditions, as found after several years of use, were used in the testing program. A thorough literature search revealed that very few studies of the behavior of complete bearing assemblies have been conducted and that specification provisions have been based on classic values of coefficients of friction between sliding parts without regard to effects of manufacturing tolerances or environmental effects. This study is an attempt to assess these effects and to provide guidelines to establish accurate estimates of horizontal force requirements for the class of bearings tested.

For the purpose of this study, the effective coefficient of friction (μ_{eff}) is defined as

where F is the horizontal force to overcome the resistance to allow motion and N is the normal force applied to the bearing. The value of F was determined experimentally for the entire assembly for an applied normal force N , from which μ_{eff} is calculated.

BACKGROUND

Many types of bearing devices are used to accommodate bridge movement: single rollers, groups of rollers, rockers, elastomeric pads, sliding plates, sliding tetrafluorethylene (TFE), etc. In general, bridge bearings can be classed in two categories: elastomeric and mechanical (1). According to a recent National Cooperative Highway Research Program synthesis on the design, fabrication, construction, and maintenance of bridge bearings (2), the elastomeric bearing pad is perhaps the best expansion bearing because it is unaffected by weather (e.g., it has no moving parts to freeze), has nothing to corrode, is low in cost, and requires almost no maintenance. However, elastomeric bearing pads are limited to 700 psi for vertical load capacity and 3 in for horizontal movement and their success depends on the quality of the material. On the other hand, for mechanical bearings the movements and rotations are accommodated by rolling, rocking, or sliding actions, usually on metal parts that can accommodate much larger bearing pressures. Furthermore, mechanical bearing devices can be designed for virtually unlimited horizontal motion (2).

One of the simplest types of mechanical bearing is the roller or "pipe roller", simply a piece of steel pipe with a stiffener as shown in Figure 1a. The load-carrying capacity of the roller is a function of its radius and can be found from the following formula (3): For diameters up to 25 in,

$$P = [(F_y - 13\,000)/20\,000] 600 d \quad (2)$$

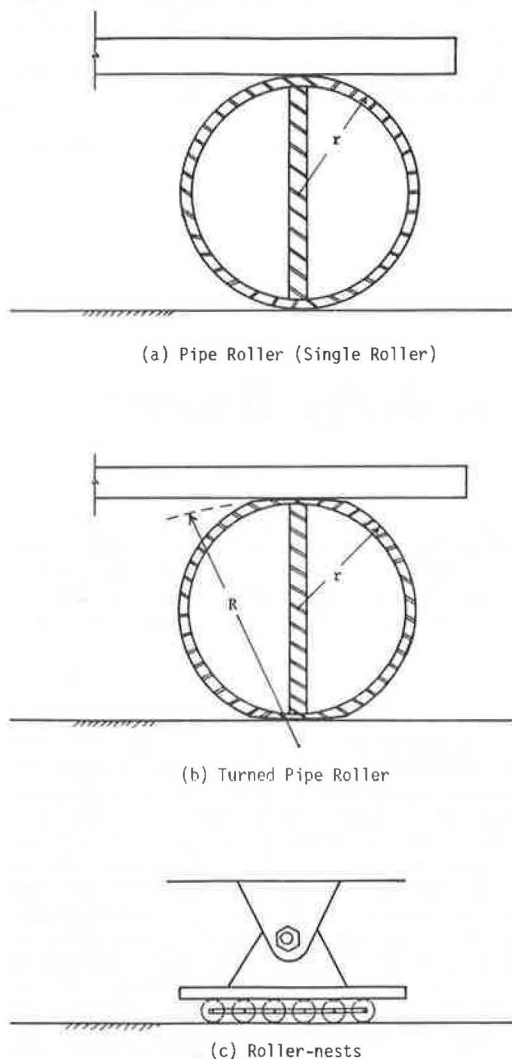
and for diameters from 25 to 125 in,

$$P = [(F_y - 13\,000)/20\,000] 3000 \sqrt{d} \quad (3)$$

where

P = allowable bearing (lb/linear in),
 d = outside diameter of the roller (in), and
 F_y = minimum yield point in tension of the steel in the roller or bearing plate, whichever is the smaller (psi).

Figure 1. Roller expansion bearing.



For a roller diameter of 12 in and a length of 12 in, the capacity of a single roller is slightly less than 100 000 lb. The principal advantage of this type of roller is the low effective coefficient of friction—generally less than 0.01 (4).

To increase load-carrying capacity without increasing the diameter, a single roller can be machined (turned) to increase the radius at the contact surface as shown in Figure 1b. This type of roller, which in this paper is called a "turned roller", has geometric properties that cause a high horizontal resistance. The equivalent effective coefficient of friction of a turned roller is a function of the amount of movement.

Rollers can be used in combination to increase load-carrying capacity, as shown in Figure 1c. Because roller nests only work well when they are clean, maintenance is required. Furthermore, this type of bearing is relatively expensive.

Several different types of rockers are used as expansion bearings: for instance, the segmental rocker, pinned rocker, and pintle rocker shown in Figures 2a, 2b, and 2c, respectively. The double-segmented rocker shown in Figure 3 has been described as a "modern rocker bearing for long steel girders" (2). Because the radius of this rocker is greater than half the depth, the resisting force

(equivalent friction force) would be tremendous for large movements.

Very few experimental studies of full-scale bridge bearings were found in the literature. Specification requirements seem to have been developed from classic values of friction coefficients and from experience. Jacobson (5) has concluded that certain pin-connection details can accumulate rust between the contact surfaces of the pin and the housing. Resulting increased horizontal forces can cause major structural damage to the main supporting members of a bridge. Laboratory tests of models similar to these bearings showed that the life of the bearing can be improved by using a case-hardened pin and by lubricating the bearing with a heavy-duty grease. Jacobson concluded that the use of pin-connected details subjected to large rotations and the use of untreated, corrosive mild steels should be avoided.

Chang and Cohen (6) have suggested coefficients of friction of 0.2 for steel bearing on steel, 0.1 for steel bearing on self-lubricating bronze plate, and 0.06 for polytetrafluorethylene (PTFE) on PTFE or stainless steel. For rocker-type bearings, they suggest that the force be calculated based on a 20 percent friction coefficient but reduced in proportion to the radii of the pin and rocker as shown in Figure 4.

British Standard 153, Specification for Steel Girder Bridges, specifies the coefficients of friction for sliding bearing as 0.25 for steel on steel or cast iron and 0.15 for steel on copper alloy. The coefficient of friction with one or two rollers is taken as 0.01.

Jacobson (7) has conducted experimental work to investigate the potential use of TFE as a sliding surface. He concluded that the TFE bearings are suitable for use as highway bridge bearings. A substantial increase in the coefficient of friction for filled TFE was found after 7000 cycles of testing.

Taylor (8) has found that the coefficient of friction of PTFE is influenced by a number of parameters, including pressure across sliding surfaces, rate of movement, presence or absence of lubrication, previous loading-movement history, and temperature. The coefficient of friction decreased with higher compressive stress across the bearing but increased slightly at lower temperatures.

SCOPE OF RESEARCH

Because few published data are available on the effective coefficient of friction of standard bridge bearings, a testing program was undertaken to investigate the performance of several types of standard ODOT bearings under several conditions. Mechanical bearing types were as follows:

1. Typical single roller bearing (Figure 1a),
2. Typical single turned roller bearing (Figure 1b),
3. Typical pinned rocker shoe (Figure 2b), and
4. Typical pintle rocker bearing (Figure 2c).

To determine the effect of environmental changes on the frictional coefficients, the following conditions were studied: (a) unlubricated (as-built condition), (b) rusted, and (c) with debris on the lower bearing plates. The unturned pipe roller, turned pipe roller, and pinned rocker shoe bearings used in the study were new bearings. The pintle rocker bearings were removed from a bridge prior to testing.

To increase the reliability of the experimental results, several increments of loading were used and

Figure 2. Rocker expansion shoes.

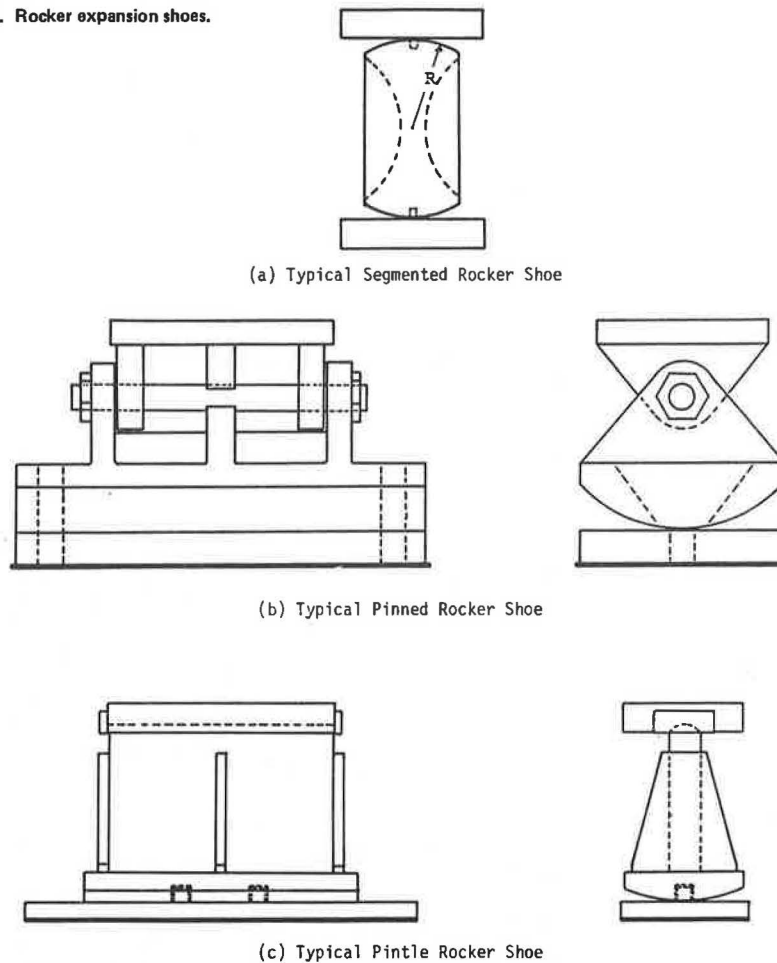
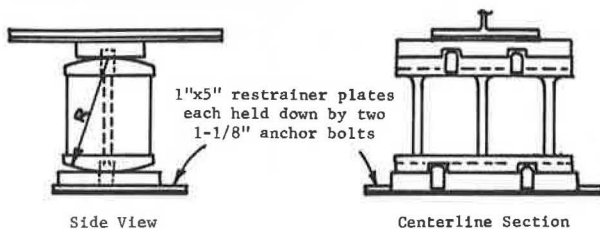


Figure 3. Double-segmental rocker.



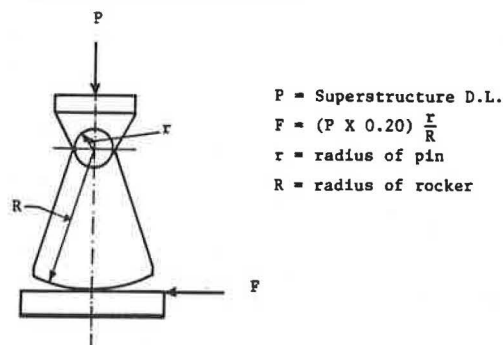
at least three tests were done at each loading for each combination.

TEST SETUP

To determine the experimental coefficient of friction of bridge bearings, a test setup that simulated the actual bridge was built as shown in Figure 5. The normal force was applied with a 750 000-lb-capacity hydraulic ram and the horizontal force with a 55 000-lb-capacity closed-loop hydraulic testing system. The data were recorded by using a microcomputer system.

The test setup was erected on the reaction floor inside the Fears Structural Engineering Laboratory at the University of Oklahoma. The setup was erected directly over two W36 beams spaced 8 ft apart and consisted of three parts: (a) an H-frame that was designed for a 250 000-lb maximum vertical reaction and that supported the hydraulic ram, (b) a

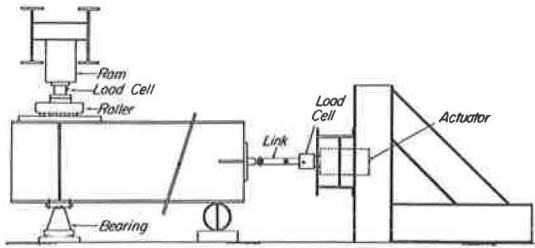
Figure 4. Forces on rocker bearings.



triangle frame that was designed for a 55 000-lb maximum horizontal reaction and that supported the closed-loop hydraulic testing system, and (c) a W33x130x15-ft girder that simulated the actual bridge girder.

The vertical load chain consisted of the H-frame, hydraulic ram, load cell, swivel head, roller nest with a known effective coefficient of friction, a steel plate with a highly polished surface, the simulated bridge girder, the test bearing, a steel reaction plate, and the reaction floor. The horizontal load chain consisted of the triangle frame, the actuator of the closed-loop hydraulic testing system, the load cell, a loading linkage to prevent out-of-plane forces, and the simulated girder (Fig-

Figure 5. Side view of test setup.



ure 5). Lateral brace mechanisms were used to stabilize the girder against out-of-plane rotations, and a pipe roller was used to support the unloaded end of the bridge girder.

INSTRUMENTATION

Instrumentation consisted of the two calibrated load cells, a horizontal displacement transducer, an analog-to-digital signal converter, and a microprocessor. The applied normal force was measured by using a calibrated 300 000-lb-capacity load cell; the horizontal force was measured by using a calibrated 100 000-lb-capacity load cell; and the horizontal movement (girder movement) was measured by using a calibrated transducer that is part of the closed-loop hydraulic testing system.

The analog signals from the three instruments were digitized by using a 16-channel differential input A/D converter with direct interface to the microprocessor. The microprocessor was used to reduce and plot the data in real time. In this manner, changes in normal force due to uncontrollable vertical movement in the vertical force chain were accounted for and the instantaneous relation of the two force variables and one displacement variable was known.

TEST PROCEDURES

For each test, the centerline of the bearing was first positioned relative to a fixed vertical plane. A nominal normal force was then applied, usually in multiples of 25 kips but not exceeding the rated capacity of the bearing. The simulated girder was then pulled at a slow rate (approximately 1 in/min) by using the closed-loop hydraulic testing system. As previously mentioned, all data were recorded in real time with the microprocessor.

Approximately 100 data sets (each consisting of one displacement and two force readings) were recorded for each test. The effective coefficient of friction was automatically calculated by the microprocessor by taking into account the initial force on the bearing due to the weight of the system and the effective coefficient of friction of the roller nest. The graphics capabilities of the microprocessor system were used to display and plot the relation between the horizontal force and horizontal movement.

To simulate in situ conditions, the steel bearings were subjected to rusting and debris environments. To achieve the rusting condition, the bearings were placed inside a closed bucket in an acidic environment for about two months. Muriatic acid (HCl) was used to accelerate the rusting. The bearings were supported approximately 10 in above the acid surface, and the bucket was kept outside where temperatures varied from 25° to 80°F.

To achieve the debris environment, an approximately 0.125-in-thick layer of graded sand was spread on the lower bearing plate. The sand, sup-

plied by ODOT, was obtained by vacuuming areas near in-place bridge bearings.

TEST RESULTS

The details of the test data for this project have been given elsewhere (9) and will not be repeated here. The essential results and conclusions are summarized below.

Unturned Pipe Roller (Single Roller)

A 10-in-diameter, unturned, stiffened, painted pipe roller (Figure 1a) was used for this phase of the study. The specimen was tested under three conditions:

1. Clean roller and bearing plates,
2. Clean roller with rusted lower bearing plate, and
3. Roller with sand spread over the lower bearing plate.

The roller was tested at four increments of vertical loading--25, 50, 75, and 100 kips--for each condition based on a load-carrying capacity of 103.5 kips, as determined from Equation 2. Typical horizontal force versus horizontal deflection plots for conditions 1-3 are shown in Figure 6. For a perfectly rigid system, horizontal displacement would not take place until the rolling frictional resistance was overcome. The initial horizontal motion shown in Figure 6 (and all subsequent similar plots) is from the elastic deformation of the test fixtures.

The results for all tests are shown in Figure 7 as effective coefficient of friction versus normal force. The straight lines shown are the result of regression analyses conducted for each condition.

The average effective coefficient of friction for condition 1 (clean roller and bearing plate) was found to be 0.33 percent with a standard deviation of 0.14 percent over 12 tests and with a range of 0.12-0.58 percent. For condition 2 (rusted lower bearing plate), the average effective coefficient of friction increased to 0.69 percent with a standard deviation of 0.10 percent over 12 tests and with a range of 0.47-0.85 percent. Approximately 0.125-in-thick graded sand was placed on the lower bearing plate in front of the roller for condition 3. In this condition, the average coefficient of friction was found to be 3.38 percent with a standard deviation of 1.2 percent for 14 tests and with a range of 2.1-5.8 percent.

From the results of the 38 tests conducted, the following results were noted:

1. The effective coefficient of friction seems to increase with increasing normal force (Figure 7). It is more pronounced for the condition with sand.
2. The effective coefficient of friction increases 400-1000 percent if sand is placed on the lower bearing plate.
3. The effective coefficient of kinetic friction is essentially equal to the effective coefficient of static friction.
4. The results for condition 2 were obtained for a rusted lower bearing plate and a clean upper plate. If the upper plate were also rusted, the increase of the effective coefficient of friction could conceivably double.

Turned Pipe Roller

A 10-in-diameter, turned, stiffened, painted pipe roller (Figure 1b) was used in this phase of the

Figure 6. Typical displacement versus friction force plots for pipe-roller bearing.

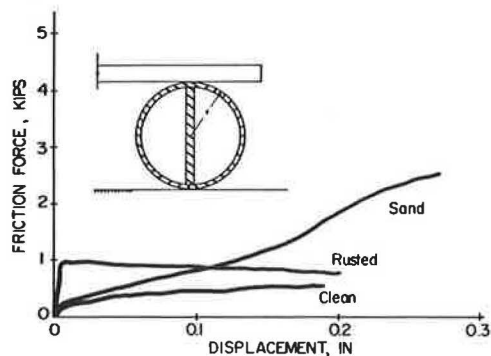
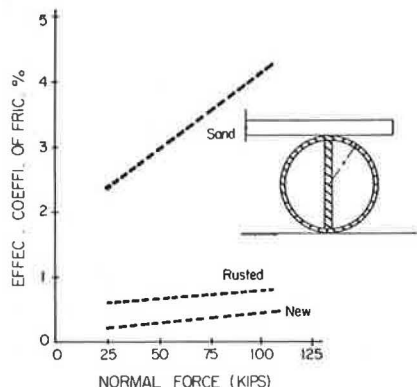


Figure 7. Normal force versus effective coefficient of friction of pipe-roller bearing.



study. The roller was identical to the unturned roller except a 12-in radius was turned on opposite sides to increase the contact surface at the upper and lower bearing plates and thus increase the load-carrying capacity. Based on Equation 2, the allowable load is 248.4 kips.

Because the radii at the two contact surfaces are greater than half the roller depth, the supported bridge girder rises slightly with horizontal movement. In addition, an eccentricity between the lines of action of the resultant vertical contact forces is therefore needed to maintain equilibrium if the roller is moved on either side of its centerline. The magnitude of this resisting force increases with movement from the centerline as long as the turned portions of the roller are in contact with the plates. Movement beyond the turned area (usually 1-2 in on each side of the centerline) results in a rapid decrease in horizontal force requirements, since the roller is essentially an unturned roller under this condition. For the purposes of this study, the resisting force is related to an equivalent effective coefficient of friction defined as follows:

$$\mu_{equiv} = F/N = (R \cdot d)/(R - d/2)h \quad (4)$$

where

R = turned radius at the contact surfaces,
 d = total depth of the roller, and
 h = total horizontal movement from either side of the centerline.

The roller was tested under the following two conditions:

Figure 8. Friction versus displacement for turned pipe roller.

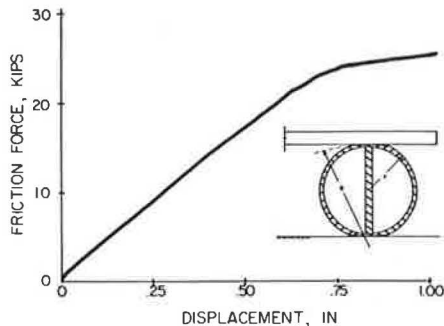
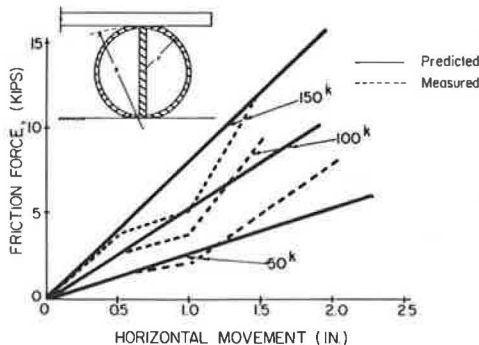


Figure 9. Resisting force versus movement for turned pipe roller.



1. Clean roller and bearing plates and
2. Roller with sand spread over the lower bearing plate.

Three increments of vertical load were used: 50, 100, and 150 kips.

Typical coefficient of friction and horizontal force versus horizontal deflection plots are shown in Figure 8. Figure 9 compares measured and theoretical results. Correlation is good except at a horizontal movement of approximately 1 in. Close inspection of the bearing showed an imperfection in the turned surface, which is believed to account for the discrepancy.

From the results of the 21 tests and the theoretical analyses, the following observations are noted:

1. The equivalent coefficient of friction is a function of horizontal displacement and increases rapidly with displacement.
2. Small imperfections in the turned surfaces can cause significant changes in the equivalent coefficient of friction.
3. The presence of sand on the lower bearing plate can increase the equivalent coefficient of friction 250-400 percent.

Pinned Rocker Shoe

A pinned rocker shoe, similar to that shown in Figure 2b, was tested for the following three conditions:

1. Clean and unlubricated,
2. Rusted, and
3. With sand spread over the lower bearing plate.

The load-carrying capacity was calculated as 232 kips by using Equation 2, and the shoe was tested in approximately 25-kip increments from 50 to 225 kips.

Figure 10. Friction force versus normal force for pinned rocker shoe.

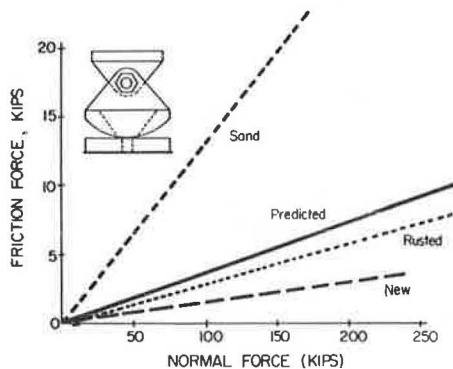
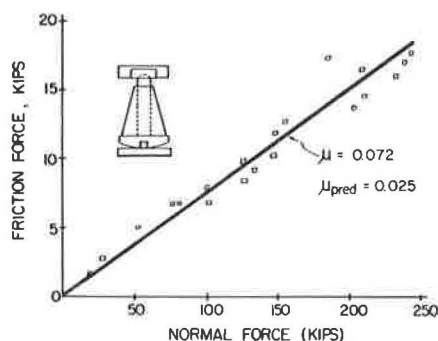


Figure 11. Friction force versus normal force for pintle bearing 1, condition 1.



The average effective coefficient of friction for condition 1 (clean and unlubricated) was found to be 0.99 percent with a standard deviation of 0.00137 over 16 tests and with a range of 0.71-1.18 percent. For condition 2 (rusted), the average effective coefficient of friction increased to 1.85 percent with a standard deviation of 0.31 percent over 23 tests and with a range of 1.38-3.23 percent. Approximately 0.125-in-thick graded sand was placed on the lower bearing plate for condition 3. The average effective coefficient of friction was found to be 8.95 percent with a standard deviation of 0.071 percent over 12 tests and with a range of 4.42-10.40 percent.

The results of all tests are plotted in Figure 10 as friction force (horizontal force) versus normal force. The straight lines shown are the result of regression analyses conducted for each condition.

The following observations are noted from the 51 tests:

1. The effective coefficient of friction for a rusted rocker can be as high as 185 percent of the value for a clean, unlubricated rocker.
2. The presence of sand significantly alters the effective coefficient of pinned rocker bearings.

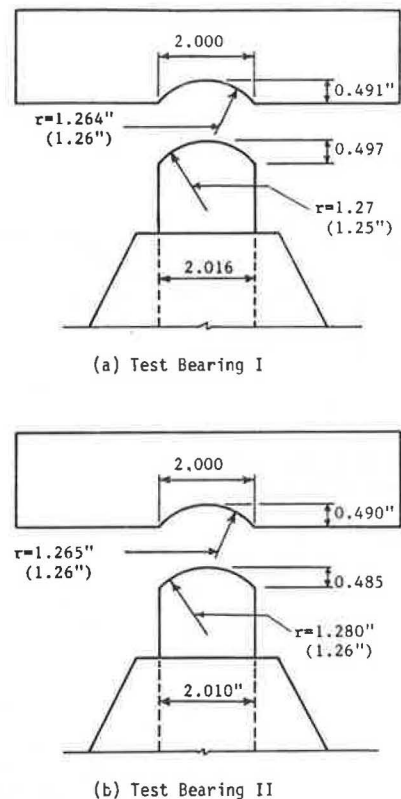
Pintle Rocker Shoe

Two pintle rocker bearings similar to that shown in Figure 2c were tested under three conditions:

1. As removed from a bridge site,
2. Partly rusted, and
3. With sand spread over the lower bearing plate.

By using Equation 2, the load-carrying capacity of the bearing was calculated to be 260 kips. Tests

Figure 12. Measured and specified dimensions of pintle rocker bearings.



were conducted from 25 to 225 kips in increments of approximately 25 kips.

Results for test bearing 1 in condition 1 (as received) are shown in Figure 11. The average coefficient of friction was 7.6 percent with a standard deviation of 0.111 percent over 24 tests and a range of 6.15-9.88 percent.

In conducting these tests, it was noticed that the bearing exhibited significantly different effective coefficients of friction depending on the initial position of the centerline of the rocker relative to the direction of movement. A series of tests for each bearing was then conducted in which the starting position was varied from before dead center to after dead center. In the 55 tests conducted, the effective coefficient of friction varied from 3.13 to 7.94 percent, a variation not found in tests of other bearings. In addition, the effective coefficient of friction predicted by the equation shown in Figure 4 was 2.4 percent.

In an attempt to determine the cause of the discrepancy, the outside radius of the top portion of the rocker and the inside radius of the sole plate were carefully measured. Actual and specified dimensions are shown in Figure 12. In both cases, the outside radius of the rocker was found to be larger than specified and larger than the inside radius of the sole plate. Because of this geometry, the top part of the rocker tends to wedge inside the socket of the sole plate, which causes a high effective coefficient of friction.

To verify this contention, sole plates with inside radii of 1.27 and 1.35 in were used for additional testing. For the series with the 1.27-in radius, the average effective coefficient of friction was 4.31 percent with a standard deviation of 0.49 percent and a range of 2.22-5.45 percent. The average coefficient of friction decreased from 7.60 to 4.31 percent with an increase in inside radius of only 0.01 in. Typical results are shown in Figure 13.

Figure 13. Friction force versus displacement for pintle rocker bearing.

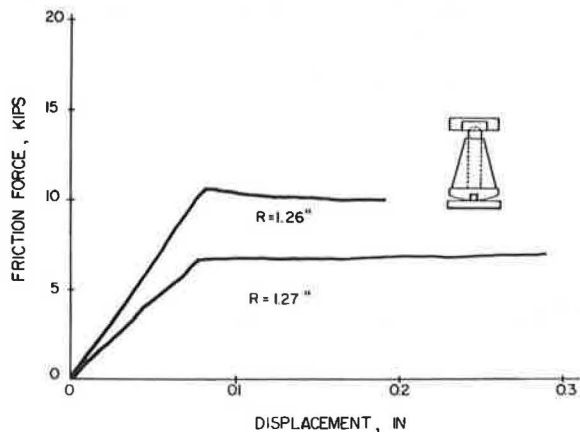


Table 1. Summary of results.

Bearing Type	Condition	Effective Coefficient of Friction		Radius of Sole Plate/Radius of Rocker (in)
		Predicted (%)	Measured (%)	
Single roller	Clean		0.5	
	Rusted		1.0	
	With sand		5.0	
Pinned rocker shoe	Clean	2.5	1.0	
	Rusted		2.0	
	With sand		9.0	
Pintle rocker	Clean	2.5	6.2-9.9	1.26/1.27
	Clean	2.5	2.2-5.5	1.27/1.27
	Rusted	2.5	3.6-5.5	1.27/1.27
	With sand	2.5	12.1-14.1	1.27/1.27

Note: For the turned roller, a geometric relation was found and sand increased the coefficient of friction 250-400 percent.

A series of tests was also attempted with a large-radius (1.35-in) sole plate. Since the radius in the sole plate was significantly larger than the outside radius of the rocker (by 0.07 in), the rocker was rolling inside the sole plate rather than sliding. The rocker was observed to roll in the sole plate socket until the required coefficient of friction was greater than that possible between the steel surfaces, and then the parts suddenly "jumped" to an initial position and the process was repeated. Results achieved by using the large-radius sole plate were too scattered to be of use.

The tests were repeated with the 1.27-in-radius sole plate for condition 2 and with the original sole plate for condition 3 (with sand). The average effective coefficient of friction for the rusted condition increased to 4.8 percent with a standard deviation of 0.18 percent over 15 tests and a range of 3.64-5.48 percent and for the sand condition to 13.13 percent with a standard deviation of 0.14 percent and a range of 12.08-14.11 percent for 12 tests.

From the numerous tests, conditions, and configurations of this phase of the study, the following observations are noted:

1. Fabrication accuracy is necessary if the predicted effective coefficient of friction (Figure 4) is used to estimate the horizontal friction force of pintle bearings.

2. Slight inaccuracies in the radii of mating parts can result in a substantial increase in the effective coefficient of friction.

3. Rust and particularly sand can substantially

increase the effective coefficient of friction of pintle bearings.

SUMMARY

The results of this study, summarized in Table 1, show that an unturned pipe roller exhibits the lowest effective coefficient of friction of the four rolling devices tested. The effective coefficient of friction was found to be less than 0.5 percent for a clean 10-in-diameter pipe roller. The value increased to about 1 percent when the roller was tested in a rusted condition and to 5 percent when sand was spread over the lower bearing plate.

Tests with a turned roller showed the equivalent coefficient of friction to be a function of the amount of horizontal movement from the centerline (median line). A geometric explanation was found, and excellent agreement between predicted and measured results was achieved.

An effective coefficient of friction of 1 percent was found from tests with a clean pinned rocker. The value increased to 2 percent for a rusted condition. Both values are lower than a predicted value of 2.5 percent determined by using a published criterion. The effective coefficient of friction for this rocker increased to 9 percent when sand was placed on the lower bearing plate.

Tests with a pintle rocker showed that fabrication inaccuracies, especially in the radius of the sole plate socket, can significantly affect the performance and effective coefficient of friction of the bearing. Tests with a sole plate socket radius slightly smaller than the rocker radius resulted in effective coefficient of friction values from 6.15 to 9.88 percent compared with 2.4 percent from published criteria. Tests with rusted bearing plates or with sand spread over the lower bearing plate showed significant increases in the effective coefficient of friction.

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Observations of Highway Bridge Movements and Their Effects on Joints and Bearings

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Data on bridge movements and their effects were collected from 314 highway bridges in 39 states, the District of Columbia, and 4 Canadian provinces. These data have been analyzed to compare the movements that occurred with evidence of structural damage and to gain some insight into the basic causes of the movements and the resulting damages. The tolerance of the bridges to the various types and magnitudes of movements was also evaluated. It was found that, in general, bridge structures have much greater tolerance to differential vertical movements than is generally thought. However, in many instances, it was found that the design and/or construction practices used led to bridges in which structural damage, particularly to joints and bearings, was produced by relatively small horizontal movements of abutments and piers and the level of these damages was more severe when the horizontal movement was accompanied by vertical movement. In many instances, it was possible to identify the cause or causes of the bridge movements and the resulting structural damage. These causes suggested possible changes in design and construction practice that could help to reduce the probability of damaging movements. It is concluded that, although many highway bridge structures can tolerate significant vertical and horizontal movements, depending on span length and stiffness, there are relatively simple design and construction techniques available that can greatly reduce the possibility of movements and thus reduce the potential for structural damage and the resulting maintenance.

Throughout the years, a great deal of data has been collected that relates observed deformations of buildings and industrial structures to structural damage. These data have then been used to establish criteria for tolerable movements that can be used jointly by geotechnical and structural engineers to decide how a structure should be founded in order to minimize costs while maintaining an appropriate level of safety against structural damage. Among the most significant published accounts of this work are papers by Skempton and MacDonald (1); Polshin and Tokar (2); Feld (3); Grant, Christian, and Vannmarcke (4); and Burland and Wroth (5). Unfortunately, however, no such criteria have been available for highway bridges. Although there is a significant body of literature dealing with the investigation of bridge approach embankments and bridge foundation movements, until recently there was virtually nothing of a specific nature in the literature that related bridge foundation movements to structural damage or dealt with the tolerance of bridges to these movements. The 1978 papers by Grover (6), Keene (7), Walkinshaw (8), and Bozozuk (9,10) and more recent papers and reports by Moulton (11), Moulton and Kula (12), GangaRao and Moulton (13), and Moulton, GangaRao, and Halvorsen (14) constitute notable attempts to remedy this situation.

As part of an extensive investigation designed to develop rational criteria for the tolerable movements of bridges, data on bridge movements, their effects, and the tolerance of bridges to these movements were collected for a total of 314 bridges dis-

tributed across 39 states, the District of Columbia, and 4 Canadian provinces. The starting point for this data collection process was the acquisition of data, contained in the files of Transportation Research Board Committee A2K03, that were the result of surveys conducted in 1967 and 1975. Supplementary data on 115 of these bridges, including as-built plans, were obtained by direct contact with the state bridge and/or geotechnical engineers who had been involved in the original surveys. In addition, data were also obtained for a substantial number of bridges that were not included in the original surveys, including 28 bridges in the State of Washington that were contained in a Federal Highway Administration staff study (15), 89 bridges from Ohio, 9 from Maine, 5 from South Carolina, and 3 from Utah.

The collected field data were analyzed to compare the movements that had occurred with evidence of structural damage and to gain some insight into the basic causes of the movements and the resulting damages. It was also possible to obtain a very important insight into the magnitude of movements that had proved to be tolerable and intolerable in actual practice.

It is the purpose of this paper to summarize the results of these analyses, to identify the most common causes of these movements and their effects on bridge structures, particularly joints and bearings, and to suggest possible changes in design and construction practice that could help to reduce the possibility of damaging movements and minimize future bridge maintenance.

INFLUENCE OF SUBSTRUCTURE VARIABLES ON BRIDGE MOVEMENTS

A general summary of the substructure data incorporated into the investigation of the influence of substructure variables on bridge abutment and pier movements is presented in Table 1. For the abutments, the variables considered were (a) general soil conditions, (b) type of abutment (full height, perched, or spill-through), (c) type of foundation (spread footing or piles), and (d) height of approach embankment. Additional variables considered for the piers were (a) span type (simply supported or continuous) and (b) abutment-embankment-pier geometry. In addition to considering the effect of each of these variables on abutment and pier movements, various combinations of variables were considered in an effort to determine combinations that may or may not result in foundation movement. A general summary of the superstructure data that have