SLIDING-UPLIFTING RESPONSE OF FLEXIBLE STRUCTURES TO EARTHQUAKES

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SUMMARY

The sliding-uplifting response of free-standing flexible structural system subject to earthquakes is calculated and discussed. The expressions for estimating the upper bound of seismic force and structural displacement of simple sliding structures have been established. The friction level at the base contact surface affects the motion style and controls the response. The flexibility of the structure affects the displacement response, and the response spectra are presented. The vertical ground motion has noticeable influence on the value of horizontal seismic force and the slip spectra.

INTRODUCTION

The slip and separation might occur in some parts of a structure during strong earthquake. There exist two different cases. One of them is referred to damage of the material in the structure. Another case is that some parts of the structural system are designed to be separable or to be able to slide. Free-standing structures and the isolation between the structure and the ground are the typical examples.

During strong earthquakes, not only the local slip and separation might occur but also the whole structure might slide or uplift. For example, the simple free-standing structures on the ground subjected to strong ground motions might slide and the seismic forces and the structural deformations would be reduced. The study of earthquake rocking motion of structure indicated that the internal forces of the structure could be reduced due to uplit. So the study of the earthquake slide and/or unplift response of structures is practically important.

Although some analytical works have been done on the problem of sliding and uplifting response of rigid bodies to earthquakes, but that for flexible structural systems is little.

This paper discusses the problem of earthquake response of flexible structural system with both sliding and uplifting motions. The behavior of simple structures with only friction sliding motion during earthquakes is discussed in detail for general case.

THE SLIDING-UPLIFTING RESPONSE OF A FREE-STANDING FLEXIBLE SYSTEM

Since reference 1 pointed out the beneficial effect of uplift to the earthquake response of a rocking structure (block), some analytical

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and experimental studies have been done on the rigid body problem. Only a few works were on the earthquake response analysis of the rocking flexible structures, and with uplift only.

Reference 2 presents the first study of earthquake uplift of a flexible structural system with both experimental and analytical works. The shaking table tests and analytical work indicated that uplift might occur when the one bay three-storey steel frame was subjected to strong ground motions and the internal forces were reduced during footing uplift. The same structure was used in reference 3 as a model to study the earthquake response of the structure with both uplifting and sliding motions. In consideration of the convenience of parametric study, the equivalent simplified model was used. There are different types of footings of the model: free-standing with different values of friction coefficients, laterally fixed to permit uplift only, and entirely fixed. For those three different cases, the same friction-separation combined element model (Ref. 4) but with different values of parameters is adopted.

Fig. 1 indicates the peak response values of different cases of footings. The values of friction coefficient vary from 0.1 to 0.8. The input earthquake is El Centro 1940 NS record. The peak acceleration is twice the value of the original as was specified in shaking table test. The results of calculation show the following facts:

(1) In the low friction range (μ=0.3), almost no uplift occurs. In the high friction range (μ = 0.5) the motion is mostly rocking uplift. For this case, there is a critical friction coefficient range near μ = 0.4± 0.1 and both the sliding and the uplifting motions are significant in that range.

(2) In the low friction range, the maximum base shear (or seismic force) can be reduced significantly by sliding compared with the fixed base case, and even with pure uplift cases. The maximum slip displacement does not necessarily decrease with increasing friction coefficient.

(3) In the high friction range, the base shear can also be reduced to a certain value by uplift. The structural displacement is much larger than that observed in the low friction range, but a large part of the displacement is due to the rocking motion and the structural deformation is not excessive.

(4) In the critical friction range ($\mu \simeq 0.4$), both slip and uplift occur, and the motion becomes complicated (Fig. 2). Structural displacement, slip and uplift all become rather large at different time instants. But the response base shear and internal forces are not greatly decreased as expected.

(5) No residual uplift will exist. But there always exists residual slip. Generally speaking, the residual slip decreases as the value of the friction coefficient increases. The residual slip in high friction case is small enough to be neglected.

(6) The accumulated slip always decreases as the value of the friction coefficient increases.

The above mentioned critical range might be wider when the imput earthquake varies. As an example, Fig. 3 shows that the critical range of the same structure is from μ = 0.4 to μ = 0.6 when the imput ground motion is Packfield 1966 N65E.

The sliding-uplifting response of complex structural system is complicated and sensitive to many parameters (seismic, structural, etc.).

But according to the above study of even limited cases, the following observations may still be made:

(1) The critical friction range should be avoided in practical design, because there is no guarantee that it will provide reduction in either force or displacement.

(2) But if high friction is specified to resist sliding for free-standing relatively tall structures, the structure will respond mostly with uplift. The internal force can be reduced by this mechanism and the structure will return to its original position (no large residual slip).

(3) Low friction device at footing to allow sliding can reduced the seismic force and structural deformation significantly.

GENERAL RESPONSE BEHAVIOR OF SIMPLE SLIDING STRUCTURES

In following two cases the structure will behave as sliding structure : tall structure with very low base friction and broad structure free to slide on the ground base. It is possible to investigate the general earthquake response characteristics of simple structures with friction sliding motion between the structure and the ground base.

The analytical study may be conducted through two approaches for that simple sliding system:

(1) To establish the basic equation of motion and solve them numerically. Different stages have to be identified during the motion of that system: before the friction at the contact surface between the structure and the ground base is overcome, the structure behaves as an ordinary vibration system; during sliding, another set of equations of motion; the equations to define the condition of starting to slide and the condiction to stop sliding. (Ref. 5)

(2) To adopt an equivalent friction element for representing the contact surface behavior. Fig. 4 indicates that the testing dynamic relationship between friction force and sliding displacement is close to a rigid-perfectly-plastic restoring force relationship, and an element have that restoring force property with varing yield level can be adopted as sliding surface model in the overall system model.
The varing strength level is specified to take into account the effect of varing normal forces at the contact surface due to the vertical ground motion. (Ref. 4)

Basic equations and numerical results show that certain general characteristics of the earthquake response of a single mass elastic system can be identified.

Seismic Force

The horizontal response acceleration of the structure, A(t), at any instant of time can be obtained from the following expression:

$$A(t) = \begin{cases} A_1\,(t) = \ddot{x} + \ddot{u} + \ddot{x}_G & \text{if } |A_1(t)| \leq |A_2(t)| \\ A_2\,(t) = \dfrac{\ddot{x} + \ddot{u} + \ddot{x}_G}{|\ddot{x} + \ddot{u} + \ddot{x}_G|}\mu(g + \ddot{y}_G) & \text{if } |A_1(t)| > |A_2(t)| \end{cases} \qquad (1)$$

where x is the relative displacement between the mass and the bottom of the structure, u is the sliding displacement, $\ddot{x}_G$ and $\ddot{y}_G$ are horizontal and vertical ground acceleration respectively, μ is the friction coefficient, g is gravity acceleration. The peak acceleration during the time history is

$$A_{max} = |A(t)|^{t}_{max} \le A'_{max} = \mu[g + (\ddot{y}_G)_{max}] , \tag{2}$$

where A'_{max} is the ideal upper bound of peak horizontal acceleration. A'_{max} will occur only when the vertical ground acceleration reaches its positive (upward) maximum value at the same time that the horizontal acceleration of the structure is large enough to overcome the frictional resistance. Usually A_{max} is smaller than A'_{max}.

The seismic force acting on the structure, F, can be expressed in terms of the friction coefficient and the weight of the structure, W. So the seismic force F of the structure will be restricted within the following limit:

$$\begin{aligned} F &\le \mu(1 + k)W \\ k &= \frac{(\ddot{y}_G)_{max}}{g} \end{aligned} \tag{3}$$

It is evident that the smaller the value of μ, the lower will be the upper bound of the seismic force. For the case without vertical ground acceleration the response acceleration will never exceed μg, i.e., the seismic force will never exceed μW. But numerical results show that the vertical ground acceleration might affect the seismic force significantly. So the vertical ground acceleration has to be considered.

Structural Displacement

The structural displacement response can also be reduced and restricted within a certain limit by sliding. For undamped elastic case, the upper limit of displacement response is given by

$$D = |x|_{max} \le \frac{\mu T^2}{4\pi^2} |g + \ddot{y}_G|_{max} \tag{4}$$

where T is the period of the structure when fixed on the ground.

Since the numerical results indicate that the vertical ground acceleration does not affect the structural displacement very much, for practical convenience, following expression may be adopted for approximately estimating the peak structural displacement values.

$$D = 25\mu T^2 \text{ (cm)} \tag{5}$$

It has very simple relationship with structure period T.

In Eq. 3 and Eq. 5, one can see that different values of μ can be chosen to specify different upper bound levels of seismic force and peak structural displacement.

Slip Response

The friction coefficient also affects the sliding displacement u significantly. Generally, the smaller the value of μ, the larger is the displacement u. So the advantage gained in reducing the seismic force and structural deformation is at the expense of a certain amount of sliding displacement between the structure and the ground. The amplitude of the sliding displacement in the response history is an important parameter in practice because appropriate measures have to be adopted according to the sliding range to permit slippage without damage to the structure.

The numerical results show that the vertical ground acceleration $\ddot{y}_G$ might affect the slip significantly. It depends upon the time histories of the horizontal and vertical ground accelerations. Figure 5 shows an example of the comparison between the response slip histories considering and not considering the vertical input.

THE SLIP SPECTRA AND THE VERTICAL GROUND MOTION EFFECTS

The numerical results show that the flexibility of the structure does not affect the acceleration response but affects the displacement response (both structural displacement x and slip u) significantly. Therefore it is necessary to formulate both structural displacement spectra S_x and slip spectra S_u (Ref. 5).

Figure 6 a and b are examples of structural displacement spectra and Figure 7 a and b the slip spectra. Both represent peak values of the specified quantities during the complete response time histories plotted versus period T.

Figure 6 show that the structural deformation increases with increasing period, T. The general trend is similar to ordinary displacement response spectra. It is apparent that the spectral displacements are smaller when the value of the friction coefficient is reduced. For El Centro earthquake, the values of S_x are about only 10% greater than that without taking into account the vertical ground acceleration. The values obtained according to Equation 5 is just in between. For Parkfield earthquake, those three are almost the same.

According to the slip spectra, maximum amount of sliding produced in a low friction case will generally but not necessarily be greater than that obtained with high base friction.

Although the slip spectrum curves don't have apparent trend associated with the period T, they all seem to have certain peak values which are in the longer period range. That means more rigid structures might have less slip response. It seems that even for the case of very low friction the slip value of rigid structure ($T < 0.3$ sec.) would not exceed the corresponding peak ground displacement very much.

It is evident that the vertical ground motion affects the spectral slip value of El Centro earthquake significantly. It might reduce but also can increase the peak slip depending upon the different values of period T. So in the general way, the vertical ground motion has to be taken into account in the spectrum calculation of the slip.

CONCLUSIONS

Different styles of motion (only sliding, sliding with uplifting and uplifting mainly) might occur when a freestanding flexible structure responds to earthquakes. The friction level of the base contact surface is one of the important parameters which affect the motion style. The seismic force and structural displacement of sliding structures can be reduced and controlled by specifying the friction coefficient value. The flexibility of the structure affects the displacement responses significantly, so it is necessary to establish the spectra of them. The vertical ground motion might affect the horizontal response of sliding structure. It has noticeable influence on the seismic force value, especially on the slip spectra.

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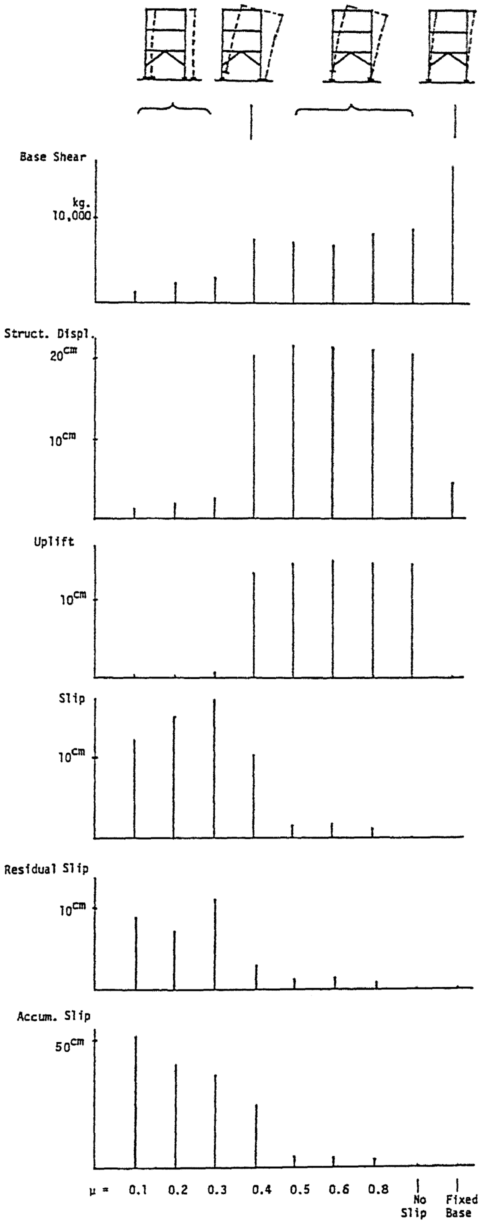


FIG. 1 Maximum Response of Structure (El Centro 1940)

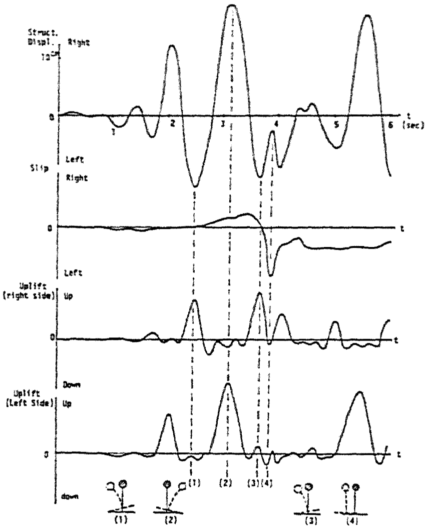


FIG. 2 Response time History of Structure ($\mu = 0.4$)

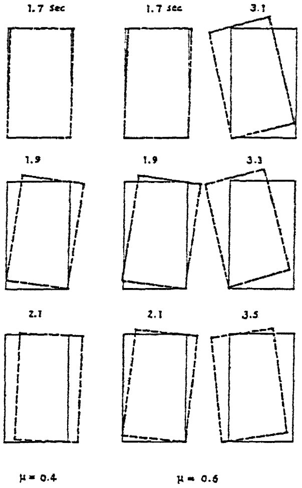


FIG. 3 Motion Styles of Response (Parkfield 1966)

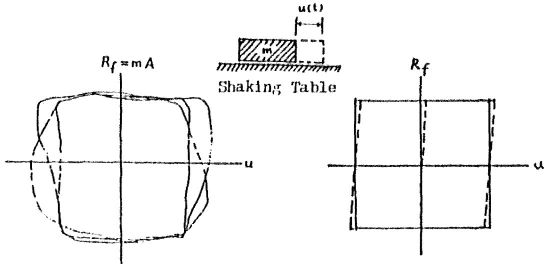


FIG. 4 Behavior of Sliding Friction

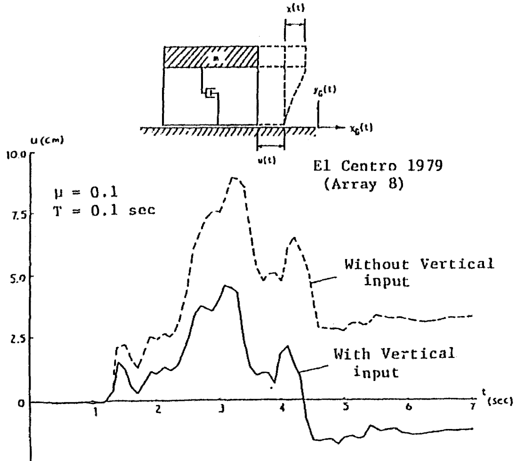
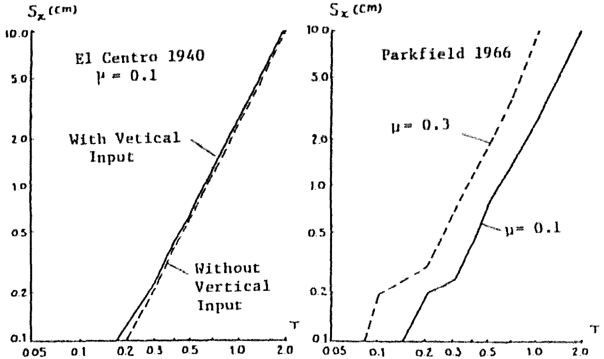
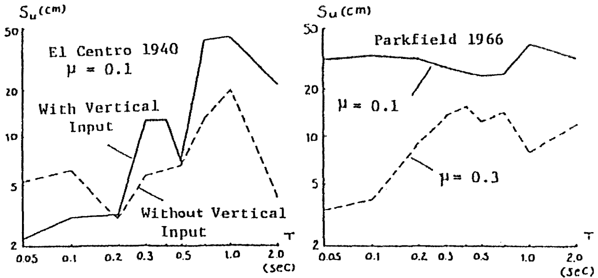


FIG. 5 Comparison of Slip Time Histories



(a) (b)

FIG. 6 Structural Displacement Spectra



(a) (b)

FIG. 7 Slip Spectra