sciendo

Civil and Environmental Engineering
Vol. 18, Issue 1, 87-95, DOI: 10.2478/cee-2022-0009

SOIL-STRUCTURE INTERACTION: COMPARATIVE REVIEW OF INTERNATIONAL CODES AND OTHER LITERATURE WITH INDIAN SEISMIC CODE

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Abstract

Currently, structural engineers design structures as fixed bases, ignoring soil-structure interaction (SSI). Due to difficulties in the modelling of soil and the absence of procedure to incorporate effects of SSI in seismic design codes. Various researchers have shown the importance of considering SSI during earthquakes. This paper highlights the interaction effects of SSI, its seismic response, the general procedure for engineers to incorporate the impact of SSI. Various methods to solve SSI problems and their provisions are mentioned in different International Seismic Codes reviewed. However, there is an urgent need to incorporate detailed guidelines considering SSI effects in the Indian Seismic code. Thus, Indian engineers should reach for international Codes or other available literature to solve their SSI assignments.

Keywords:

Soil-structure interaction;
Kinematic interaction;
Inertial interaction;
Direct method;
Substructure method.

1 Introduction

After the San Fernando earthquake 1971, most countries considered the effects of soil-structure interaction (SSI) for extensive research. Mylonakis, G. and Gazetas, G. [1] have concluded that in the 1995 Kobe earthquake, SSI is one of the main reasons for the collapse of the Hanshin Expressway. These damages led to a need to analyse the behaviour of the soil under earthquake action. The Soil-Structure Interaction is the dynamic inter-relationship between the response of the structure and soil. The behaviour of soil and vice-versa affects the motion of the structure. The seismic response of the soil, foundation, and structure subjected to a free-field ground motion is assessed by SSI analysis. The effects of SSI have become a significant part of structural engineering during the construction of massive structures, particularly on soft soils like dams, nuclear power plants, retaining walls, bridges, etc. Conventional design of buildings, the effect of flexibility of the foundation and the soil is not considered in the design procedure. It leads to an unsafe design method of the structure. Thus, it is essential to evaluate the effect of SSI in the seismic design. In this paper, interaction effects of SSI, classification of various methods to model effects of SSI, and design guidelines for SSI by different international design codes are elaborated. The main concern is the Indian Seismic design code, which does not provide detailed design procedures to model SSI effects. Thus, knowledge and practical application gap in the design of structures due to a lack of guidelines in seismic design codes are identified.

The SSI became a part of the performance-based evaluation in recent studies, particularly in retrofitting existing structures. Also, the study about SSI focus on the structures attached with base isolators, tuned mass dampers, and other equipment to reduce the effect of lateral forces. Dao, N. D. and Ryan, K. L. [2] assessed SSI effects on the base-isolated building with friction bearings.

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Researchers also study the structure-soil-structure interaction (SSSI), and it considers the pounding effect of adjacent structures in soft soil. Elwardany, H. et al. [3] studied the influence of SSI on pounding of the steel frame buildings. Awchat, G. D. and Monde, A. S. [4], working on the structure's behaviour during the El-Centro earthquake, taking soil-structure interaction (SSI) into account. The time-history approach is used to determine the seismic response of a G+10 storey building in various seismic zones across India. The influence of SSI is studied using a direct approach, namely finite element analysis. Drusa, M. et al. [5] investigated geotechnical parameters and acceptable solutions to get a suitable and safe design. The Monte Carlo simulation approach is identified to evaluate geotechnical parameters.

2 Interaction effect due to SSI

There are two types of interactions that affect the seismic response and performance of the structure due to interaction between soil, foundation, and structure. Kausel, E. [6] introduced kinematic and inertial interactions. Scattering, reflection, and propagation of seismic waves at the foundation and soil interface due to foundation incapability to match free-field motion is kinematic interaction. It deals with the ground motion and differentiates between foundation input ground motion (FIM) and free-field motion. When the structure and foundation have no mass, the motion produced at the base slab is called FIM. But in practical conditions, the mass of the structure and foundation produces inertia due to acceleration caused during an earthquake. These forces try to move the soil below the structure, and the soil then transmits it to the foundation is inertial interaction effect. Displacement and rotation are produced at the interface of soil medium and foundation. The most critical factor controlling the inertial effect is the structure-to-soil stiffness ratio, represented in equation (1).

$$\textit{Structure-soil stiffness ratio} = h/(v_s \cdot T). \quad (1)$$

In equation (1), h is the height of the centre of mass of building in first vibration mode shape, v_s is the shear wave velocity, and T is the fundamental time period corresponding to the fixed-base structural model.

3 Method of analysis of SSI problems

Initially, the analytical methods are not used and are not acceptable due to their complexity and high computational costs. Then the experimental procedures were carried out, like shaking table tests and centrifuge modelling. The physical methods are used to validate the numerical methods. Qaftan, O. et al. [7] carried out experiments on physical models to validate the finite element-based numerical method. Wolf, J. [8] classified the methods for analysing SSI based on the behaviour of soil and structure, i.e., linear or nonlinear. Further, the classification is based on boundary conditions as direct and substructure methods. Far, H. [9] identified the most precise and reliable modelling technique and compared the advantage and disadvantages of each technique. He concluded that numerical methods are most accurate as these methods can incorporate various material conditions and damping, stress anisotropy, changes in the geometry of soil, and radiation damping to analyse the dynamic nature of SSI.

The linear or non-linear nature of the soil medium depends on the nature exhibited by the element used in the analysis. The non-linear nature includes material and geometric nonlinearities in soil, foundation, and structure. Further, to analyse linear and non-linear nature, the methods are classified as time and frequency domain. The time-domain methods study soil's nonlinear behaviour and pore water pressure effects. The non-linear nature at the interface of structure and soil is also considered. Khanmohammadi, L. et al. [10] performed the analysis in the time domain. The frequency domain considers only linear behaviour. When the structure and soil exhibit linear behaviour and highly developed procedures are used, it is in the frequency domain. The frequency-domain method is more accessible than the time domain method for solving SSI problems. NIST [11] classified the methods to solve SSI as direct and substructure methods based on its interaction effects. Various researchers compared the performance of direct and substructure methods. The different methods to model the structure with SSI are shown in Fig. 1.

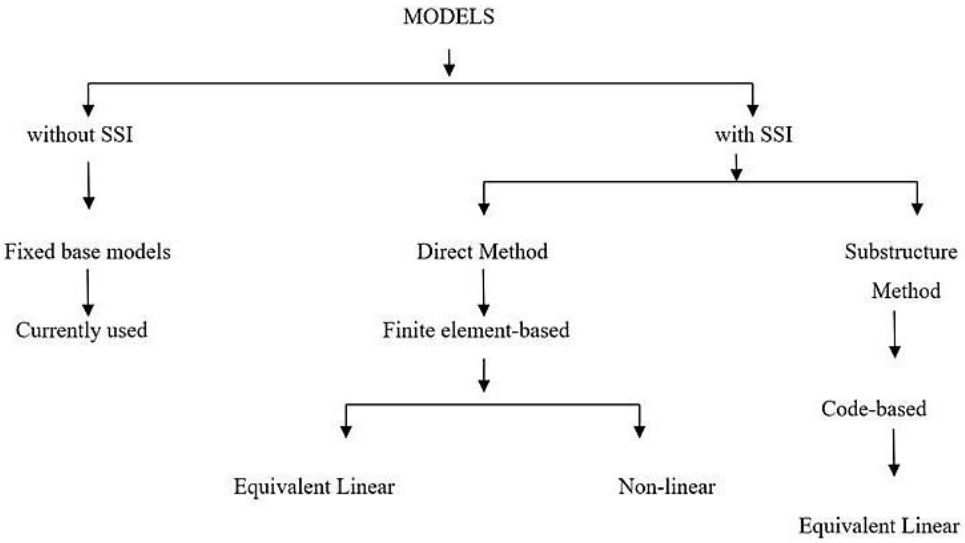


Fig. 1: Different methods to model structure with SSI.

3.1 Direct method

In the Direct method, the soil is included in the system for modelling and analysis. In Direct analysis, the soil is signified as a continuum in the form of finite elements. It has soil, foundation, and other structural parts transmitting boundaries and interface elements. Transmitting boundaries are located at the edge of the filthy mesh, whereas the interface elements are at the end of the foundation. Incorporating the kinematic interaction is a problematic indirect method as it requires the description of spatial variable input motion in all three dimensions. The calculation of the solution of the direct method is complicated when there are complex structures or they have nonlinear soil and structure properties. Fig. 2 shows the direct method of SSI using finite elements.

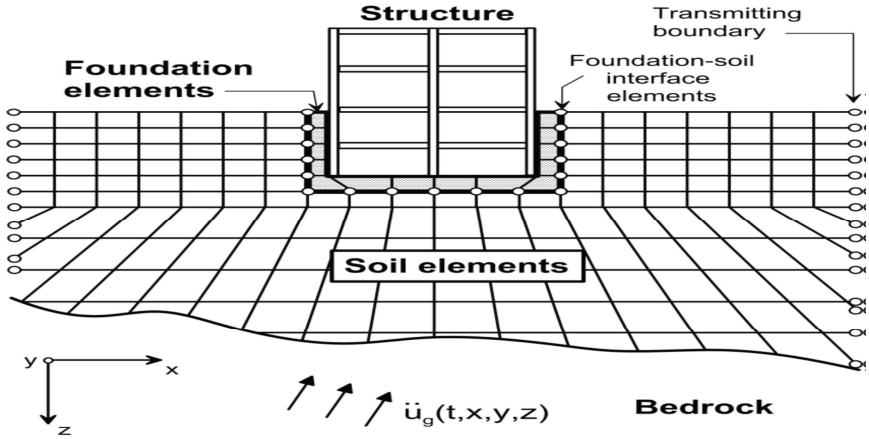


Fig. 2: Direct method of SSI by using finite element [8].

3.2 Substructure approach

The SSI problem is separated into different parts in the Substructure method to form the solution. Transfer functions evaluate the kinematic components, and impedance functions separately assess inertia components. The main steps involved in the analysis are as follows:

- Calculate free-field soil motions and their related soil properties.
- Determine transfer function to change free-field motion into foundation input motion.
- Incorporate spring, dashpot, and another non-linear element which shows the soil properties like damping and stiffness located at the interface of soil-foundation. It is called an impedance function.
- Perform dynamic analysis on the whole soil-structure system considering FIM.

3.3 Different analysis methods

Various methods are used to predict stresses, rotation, and lateral deflections. It can be classified as the Winkler method, P-y method, and elastic continuum method as per Yesane, P.et al. [12].

3.3.1 Winkler model

As per Bowles, the Winkler model shows soil medium in the form of closely spaced, discrete independent, as well as linearly elastic springs [9]. When a load is applied to the limited area, deformation of the foundation takes place. Fig. 3 shows the model of the Winkler foundation. The relationship between pressure and deflection at any point is represented as in equation (2).

$$p = k \cdot w, \tag{2}$$

where p, k, and w denote pressure, coefficient of subgrade modulus, and deformation, respectively.

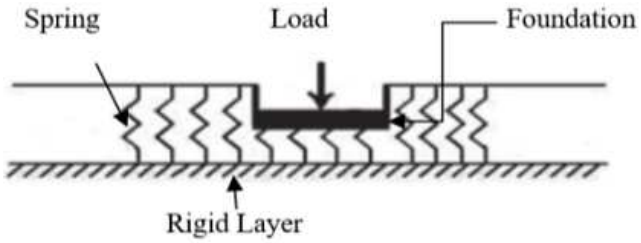


Fig. 3: Model of Winkler foundation.

Various models were developed, like the Pasternak model, Vlasov model, Kerr model, etc., to overcome the limitations of the Winkler model. The Winkler model takes into account the only modulus of subgrade of soil, but the Pasternak model takes into account both modulus of subgrade of soil and shear interaction effect. The Pasternak model shows more accurate soil conditions than the Winkler model. Bao, T. and Liu, Z. L. [13] evaluated Winkler and Pasternak model as partially embedded soils and recommended using the Winkler model to predict better predominant natural frequency.

3.3.2 P-y method

It simulates the resistance of the soil in the form of non-linear springs. P represents the pressure of the soil per unit length, and y represents the deflection of the pile. P-y curves describe the non-linear behaviour of the soil that has a different depth and type of soil. Factors like soil type, dimension and shape of foundation, loading type, boundary conditions and method of construction of a foundation, coefficient of friction between soil and foundation affect the P-y method.

3.3.3 Elastic continuum approach

The nature of the soil is idealized as three-dimensional continuous elastic solid, isotropic, and semi-infinite. Deflections will be under and surrounding the loaded area. The layer effects of soil and its anisotropy are easy to consider in this approach. A continuous function denotes the behaviour of soil.

3.4 Numerical methods

Drastic change due to the advent of the computer in mid-1960 - the 1970s, the numerical methods have modified analytical methods [6]. The analysis of the rigid circular disk, irregular shapes, flexible foundations in inhomogeneous or layered media, and effects like the inelasticity of the soil can be considered easily in FE software like Abaqus, Ansys, Open Sees, SAP 2000, ETABS, etc. The boundary element method, i.e. a numerical method, helps study complex interactive behaviour based on integral boundary equations. The finite element method is more significant and widespread for complicated problems than the boundary element method. Numerical methods are highly recommended to obtain exact and practical results for dynamic soil-structure analysis.

3.4.1 Finite element method (FEM)

FEM is beneficial for analysing the SSI effect with accuracy as it considers the non-homogenous and nonlinear effects of the material. It utilizes the variation principle to solve the particular governing equation and boundary conditions. The model is divided into several small parts. This method helps solve an extensive range of practical problems. The equi-dimensional Finite element analysis is used for modelling SSI problems. The three-dimensional analysis is used for large projects for highly complex soil models. Its significance is that the foundation's entire stress distribution can compute for research. In FE analysis, implicit and explicit dynamic analyses are used to understand the structure's dynamic behaviour.

Table 1 shows an application of various FE software in different research related to SSI. Software like Abaqus, Ansys, and SAP 2000 provides the user to model the realistic nature of soil using the geotechnical properties of the soil like Elastic modulus, Poisson's ratio, and Shear modulus, etc. This software also provides the option to define the inhomogeneous nature of the layered soil. Some of the limitations of FEM are as follows:

- Selection of correct element size is difficult.
- The results of numerical analysis of wave propagation phenomenon are susceptible to boundary conditions.
- It can obtain approximate solutions only.

Table 1: Application of various FE software in different research related to SSI.

Software	Foundation	Purpose	Reference
Abaqus v.6.8.	Mat foundation	The seismic analysis of buildings on sandy soil considering SSI was performed to evaluate stress propagation, amplification, and acceleration response at the foundation and soil medium interface.	Matinmanesha, H. and Asheghabadib, M. S. [14]
OpenSees	Shallow foundation	The efficiency of the base isolator evaluated on residential base-isolated buildings with SSI effects considering the non-linear behaviour of the base isolators and soil deformability effects.	Forcellini, D. [15]
C++	Piled Raft foundation	The seismic analysis of asymmetrical buildings with SSI effects observed that shape of the structure affected seismic response under the Nepal earthquake in 2015.	Bardy, P.and Satyam, N. [16]
Abaqus	Pile foundation	The FE analysis was validated using a shaking table test on the structure of soft clay.	Al-Isawi, A. T.et al. [17]
Ansys 14.5	Mat foundation	The SSI effects were evaluated on multi-story buildings and observed that with the interaction of foundation and soil elements, response of structural changes.	Jha, et al. [18]
SAP 2000	Pile foundation	High-rise building with and without soft stories considering SSI effects analysed. The seismic response and fragility curves describe various damage states to the structure evaluated.	Samanta, A.and Sriwastav, R. K. [19]

3.4.2 Boundary element method (BEM)

This numerical method was developed after FEM. The boundary of the considered domain is discretized in this method. The advantage of BEM over FEM is that it needs discretization of the surface, and then the radiation condition is automatically satisfied. Therefore, researchers use BEM more than FEM. It is the most suitable method for propagating seismic waves in complex soil mediums.

3.4.3 Spectral element method (SEM)

The SEM formulation is similar to that of FEM. SEM uses Discrete Fourier Transform (DFT) to transfer the partial governing equations from a time domain to a frequency domain. It reduces finite elements, degree of freedom, time, and space for computation. Boudaa, S. et al. [20] validated the SEM method to differential transform method and analytical method and concluded that it converges fast than FEM and the soil property affects the mode shapes of vibration.

4 Procedure to incorporate effects of SSI

Waqas, M. and Ali, M. [21] discussed a procedure used in current practice by structural engineers to incorporate effects of SSI in the design. The steps to consider only the effects of a flexible foundation are given below, and the kinematic effects of the SSI software like Abaqus, OpenSees, and Ansys are used.

- The geotechnical parameter was evaluated.

- The Finite element model with a fixed base is prepared using software like ETABS, SAP 2000, etc.
- The structure-soil ratio $h/(v_s \cdot T)$ is calculated. If it is greater than 0.1, then the SSI has a significant effect on the structure, and if it is less than 0.1, then the SSI effects are significantly less.
- Then, the foundation is designed by using springs and dashpots.

5 Different international codes and standard provisions for effect of SSI

The design codes practice the over generalized design spectra; in this, the up to specific period uniform acceleration is achieved, and after that, it reduces with time. The nature of the structure becomes flexible by including the SSI effect. Mylonakis, G. and Gazetas, G. [1] observed that the increase in the natural time period is not always beneficial, given by the generalized design spectrum. The period of earthquake waves can be elongated by the soft soil sediments, increasing the structure's natural time period. It leads to the resonance effect along with long-period ground vibration. The ductility demand is also increased significantly with the natural time period with SSI. The seismic response of the structure is worsened by permanent distortion and then failure of the soil. Fewer provisions are available in codes and standards to consider the effects of SSI. The guidelines present in international codes and standards are as follows:

- ATC 3-06 started the provisions of SSI in 1978. It suggests decreasing the design base shear. This decrease in equivalent lateral force depends on the elastic structural response. Still, further, it knew that the effects of SSI on the structure's reaction reduce along with the extent of inelasticity felt by the structure. Due to this, the structure is inadequate to perform safely during an earthquake.
- ASCE 7-10 introduced base shear reduction and suggested the modification in design base shear not less than 70 % of the original base shear value. Jarernprasert, S. et al. [22] observed that the mean ductility demand exceeds target ductility for the structures designed according to ASCE 7-10. From this, it can be known that there is a need for reconsidering the provisions given in ASCE 7-10.
- ASCE 7-16 recommended a decrease in base shear for structures with more considerable response modification with greater inelastic deformation capacity. This code also allows the linear dynamic analysis and procedure of equivalent lateral force by modification of SSI design response spectrum given in code; otherwise, by modification of SSI site response spectrum, it is provided by the structural engineer. The effects of kinematic interaction do not incorporate with linear dynamic analysis. If kinematic interaction is prevalent, then acceleration history data's nonlinear response history analysis scaled to a site-specific response spectrum is allowed.
- National Earthquake Hazard Reduction Program (NEHRP) gave the guidelines to consider the effect of SSI in the form of FEMA 450. The response modification factor was introduced by FEMA 450 to limit the decrease in base shear. FEMA 450 considered the effect of foundation flexibility and recommended using equivalent linear stiffness. It requires seismic foundation input motion which is further modified in FEMA 440. FEMA P-2091 concluded that SSI is not difficult to implement and focused on additional rounds of analysis compared to fixed base analysis to converge on the final solution.
- Eurocode EN: 1998-1 referred to the ground type with high plasticity index and deficient shear strength. Eurocode EN: 1988-5 considers the dynamic SSI effect for the slender structures or the structures with significant second-order ($P - \delta$) effects. This code made it compulsory to include SSI effects in design, but it does not provide guidelines to calculate them. The structures rested on the piles or with massive seated foundations like offshore caisson and silo, and bridge pier should allow the effect of SSI in the design.
- IS 1893: Part 3 and Part 4 gave information about SSI for designing bridges and industrial structures. The effect of SSI should incorporate into the design of these structures if it is resting on deep foundations and soft soil. Although, it is seen that the effect of SSI leads to reduction of seismic forces and increased lateral deflections. Also, for the computation of SSI, no detailed guidelines are provided. Other parts of seismic codes, i.e. IS: 1893, Part 1 and 2 which deal with general buildings and liquid retaining structures, do not mention the effect of SSI or its design procedure. It does not refer to any other code to consider the effects of SSI.
- JSCE 15 Code is used to design retaining walls, abutments, underground structures, and foundations like caissons and piles. The dynamic effect of the interaction of the ground and structure must be considered while designing foundations. For all other structures, the effect of SSI is ignored. Otherwise, it can be modeled depending on characteristics and type of soil and structure.

- NZS 1170-5 does not give any guidelines to include the effects of SSI in design. But it consists of the term structural performance factor depending on the form, material, damping, period, and interaction of the structure with the ground. This code also necessitates consideration of foundation deformation while calculating the deflection of the building.

The ASCE 7-10 and ASCE 7-16 reduced the design base shear with the increased time period and effective damping ratio by considering the smooth idealization of the design spectrum. This effect applies to the linear soil-structure system rather than yielding systems. Khosravikia, F. et al. [23] determined the structure's response, including results of SSI in the design from ASCE 7-10 and NEHRP 2016 edition. The observations showed that SSI guidelines for both NEHRP and ASCE 7-10 resulted in hazardous effects for the structures with medium-soft soil on surface foundations. For squat structures, NEHRP advances the current guidelines. Both the codes obtained a conservative design, but NEHRP gave a more traditional design. For all other systems, Upadhaya, A. and Verma, A. [24], approached yield near-optimal results. ASCE 7-16 is the most progressed code in applying SSI in structural engineering practice from all these codes. The American and Japanese provisions are more developed from the SSI point of view. As the American codes provide a procedure for designing SSI and other linear modelling procedures, Japanese codes use constitutive models and the non-linear nature of an interface. But the Indian Seismic code does not provide any particular guidelines to incorporate the effects of SSI in the analysis and design of the structures. However, the FEMA P 2091 can be used by Indian engineers to study the importance of SSI and with examples for implementation of SSI. This standard provides a clear and easy understanding of the SSI effects in the design of structures.

6 Need to include design guidelines in Indian seismic code

It is essential to consider the effects of soil-structure interaction for the structures resting on the soft soil. To show the importance of including SSI in the Indian Seismic code of design, Sharma, N. et al. [25] evaluated the differences in the design and analysis due to neglecting the effect of SSI. The five different types of analysis are carried out on the structure as follows:

1) Equivalent Static Method (ESM): The base is kept fixed, and the design force is calculated by the procedure mentioned in the standard design code.

2) Fixed Base Analysis (FBA): The base is fixed at the bottom, and the design force is calculated by the spectrum compatible motion.

3) Linear Soil-Structure Interaction (LSSI): The soil and foundation are designed with a superstructure. The spectrum compatible motion, equal to half of peak ground acceleration, is used as input at the base.

4) Nonlinear Soil-Structure Interaction (NLSSI): This method is similar to LSSI. The difference is that nonlinear properties of soil are used for the analysis.

5) Fixed Base with Free Field Motion (FBFFM): The modified motion is affected by the presence of soil. It is recorded at the top of the soil medium. The base is kept fixed in this analysis.

6) It observed that the design forces calculated by the ESM method are significantly less than the actual design force due to SSI effects. The FBA produces a considerable force than the actual design force. The forces produced by LSSI and NLSSI are somewhat more significant than ESM. Both the ESM and FBA give unrealistic design forces. Hence, it becomes necessary to include SSI in the structures located on soft soils.

7 Conclusions

The present study reviews different methods to model SSI and the current procedure to incorporate SSI provisions in other International Seismic codes. It needs to include it in the Indian Seismic Design code. The following are the conclusions based on review:

1) The Substructure method's modelling is more comfortable than the direct mode, but the direct way gives accurate results.

2) To consider the SSI effects, at least the Winkler model should be used as numerical methods whereas FEM and BEM are tedious.

3) The ESM and FBM method of analysis gives unrealistic design forces. Hence, it is necessary to include SSI effects, particularly in soft soils.

4) The current procedure used by Indian structural engineers is reviewed, but there is still ambiguity to design the structures considering SSI effects.

5) There are no proper provisions in the Indian Design code as in ASCE 7-16 and a lack of conversation between geotechnical and structural engineers.

6) It is essential to consider the SSI effects in the buildings' design and retrofitting for the structures' safe design. It can be achieved by including proper provisions in codes and selecting the appropriate SSI method.

Acknowledgements

The authors would like to acknowledge Shri Guru Gobind Singhji Institute of Engineering and Technology, Nanded, Maharashtra State, India, for providing excellent state-of-the-art central library facilities to refer peer-reviewed journals to prepare a paper manuscript.

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