A METHOD TO INCLUDE SOIL-ABUTMENT INTERACTION IN NONLINEAR ANALYSIS OF BRIDGES

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Abstract

With the aim to include the seismic response of the abutments into the global structural analysis of a bridge, this paper describes a new macro-element of the soil-abutment system. The model is conceived to reproduce the multi-axial force-displacement relationship at the deck-abutment contact, accounting for the frequency-dependent inertial effects and the nonlinear behaviour of the geotechnical system, keeping at the same time a high computational efficiency. The formulation of the macro-element was coded as a new finite element in the analysis framework OpenSEES. A calibration procedure of the proposed model was devised, based on the results of nonlinear static and dynamic analyses on a reference soil-abutment system implemented in OpenSEES.

Keywords: dynamic soil-abutment interaction, macro-element approach, inertial effects, non-linear response, implementation.

1. Introduction

The soil-abutment interaction is usually neglected in the structural analysis of bridges because of the complexity associated with this phenomenon and for the lack of analysis methods that, on the one hand, provide a sufficiently detailed description of the abutment response and, on the other hand, limit the computational demand of the soil-structure models. In fact, a bridge abutment interacts with a large volume of soil through its foundation and wall. The resulting global response can exhibit highly nonlinear features and pronounced inertial effects under severe ground shaking with important repercussions on the performance of the whole bridge structure [1]. Some empirical models are available in the literature to reproduce in numerical computations the nonlinear longitudinal response of the abutment and the attainment of the passive limit conditions in the backfill [2,3]. Following a completely different approach, Kotsoglou and Pantazopoulou [4] developed an analytical model to study the frequency-dependent response of bridge abutments, under the assumption of a linear soil behaviour. In the present paper, we propose an alternative method of analysis based on the introduction of a macro-element representation of the soil-abutment system in the global model of the bridge structure. The macro-element is conceived to combine the nonlinear response with the simultaneous activation of inertial effects in the geotechnical system. The macro-element is initially described in its essential characters. Then, its use in the analysis framework OpenSEES [5,6] is illustrated. The full soil-bridge model of a multi-span girder bridge recently implemented in the OpenSEES environment by Gorini and Callisto [7] is taken as a reference to provide a quantitative evaluation of the main features that constitute the macro-element: from the full model shown in Figure 1, a local model of the strong abutment was developed to test the response of the macro-element under multi-axial loading conditions.

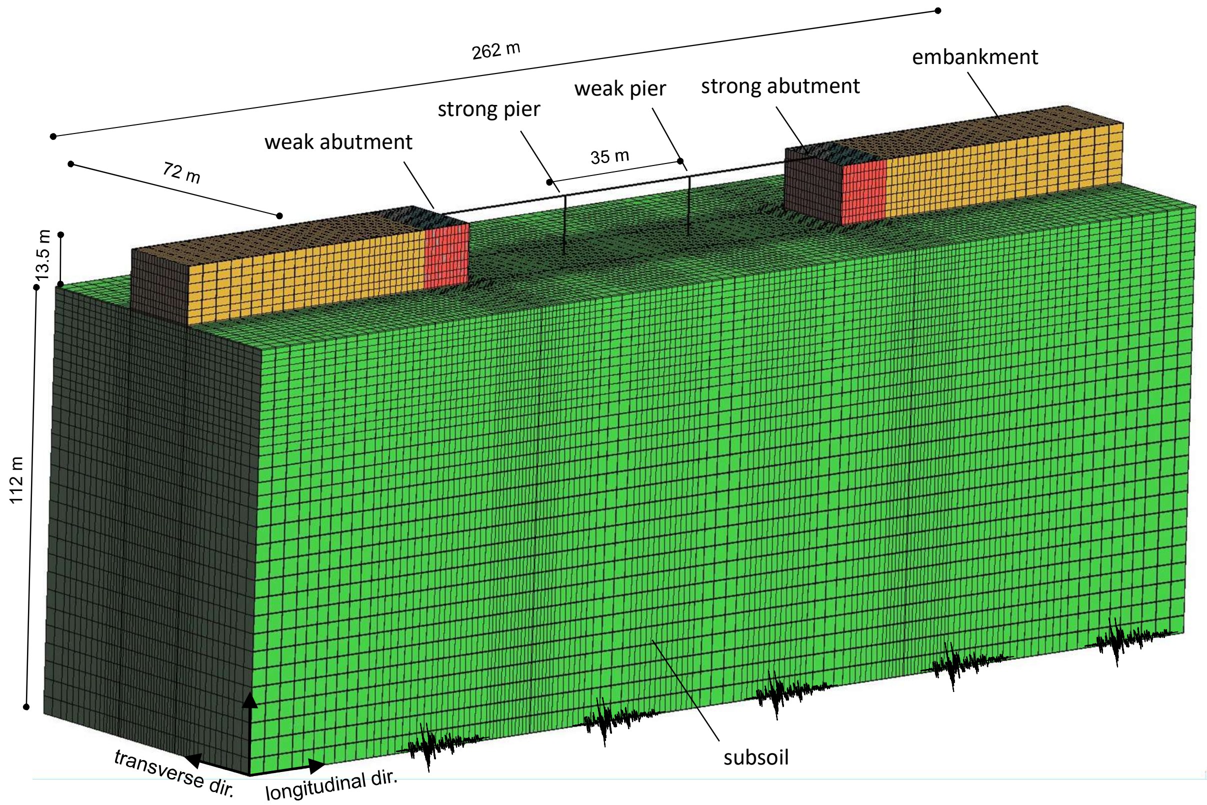

Figure 1. Reference soil-bridge model implemented in OpenSEES.

2. Conceptual framework

The macro-element of the soil-abutment system is conceived as a multi-axial, nonlinear relationship between the interaction forces Q_i exchanged at the deck-abutment contact and the corresponding displacements q_i, that simulates the response of the abutment and of the large volume of soil interacting with it. The focus is on semi-integral abutments (hinged bearing devices supporting the deck) for which moment transmission on the abutment top can be reasonably neglected.

The force-deformation relationship of the macro-element is a macro-constitutive law of the geotechnical system that reflects the most salient effects of soil-abutment interaction. With this approach, a combined nonlinear and inertial response of the abutment can be reproduced simultaneously within a rigorous plasticity-based formulation. The macro-element was developed as a multi-surface plasticity model with purely kinematic hardening, in which the latter is an essential feature for a proper reproduction of the cyclic response of the abutments. The constitutive law was derived within a rigorous thermodynamic framework in order to ensure the energetic compatibility of deformation processes; the reader can refer to [1] for a detailed description of the mathematical formulation. In the following, the two key aspects that define the structure of the macro-element are described, that are the identification of the plastic domain and the inclusion of the inertial effects of the soil-abutment system.

2.1 Plastic domain

The plastic domain is intended as the region in the space of the interaction forces Q_1-Q_2-Q_3 (longitudinal, transverse and vertical force, respectively) at the deck-abutment contact of admissible states for a soil-abutment system. With reference to the abutments of the model in Figure 1, Gorini et al. [8] found that the plastic domain is bounded by the ellipsoidal ultimate yield surface shown in Figure 2. This surface represents the locus of ultimate conditions for a semi-integral abutment because it was retrieved as the force combinations {Q_1-Q_2-Q_3} that activate global plastic mechanisms of the system. Within the ultimate surface the response of the macro-element is elastic-plastic starting from a very small first yield surface (Fig. 2), homothetic to the ultimate surface, within which the behaviour is linear elastic. The transition from the first yield to the ultimate locus is controlled by a series of internal yield surfaces that are assumed to be homothetic to the two surfaces described above. During plastic loading, the internal yield surfaces evolve in the force space according to a prescribed translation rule [1] that reproduces the kinematic hardening effect.

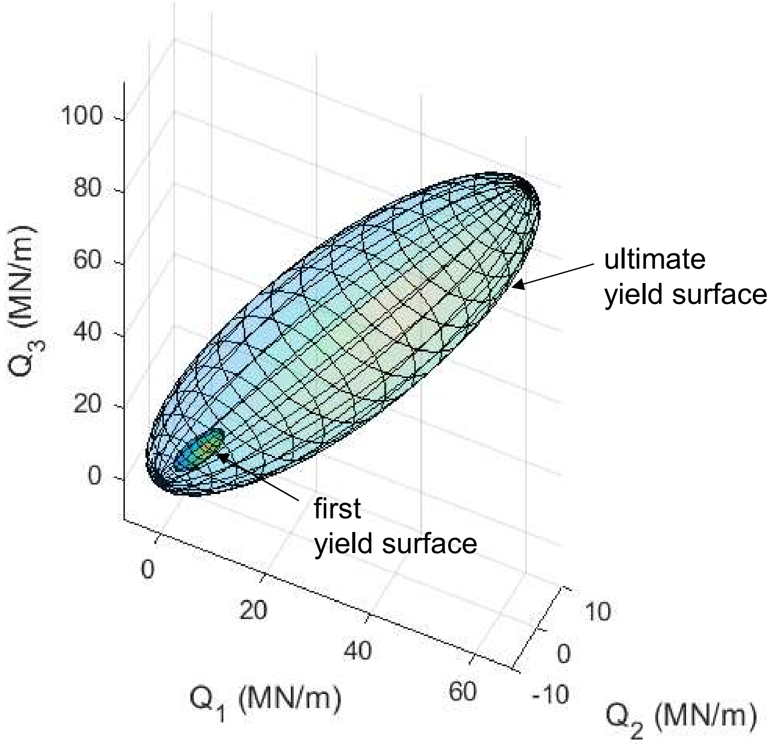

Figure 2. Boundary surfaces of the plastic domain of the macro-element in the Q_1-Q_2-Q_3 space.

2.2 Inertial effects

Under dynamic conditions, the inertial forces that develop in the abutment structure and especially in the volume of soil that participates to the dynamic response can considerably alter the global behaviour of the bridge. These effects are enclosed into the macro-element formulation through the introduction of additional mass tensors, which are thought to represent the participating modal masses of the soil-abutment system along the three coordinate directions of the deck-abutment contact (longitudinal-transverse-vertical). In principle, each yield surface is associated with a mass tensor, even if it was demonstrated that a limited number of masses can be sufficient to reproduce with a good accuracy the frequency-dependent amplification of the abutment response from small to large strain levels [1]. More in detail, the first mass tensor associated with the surface of first yield, related to an essentially reversible response of the soil-abutment system, is the most crucial component in the calibration of the macro-element: it is aimed to localise the dynamic amplification in correspondence of the fundamental vibration period of the abutment at small displacements, while the other mass tensors, that are activated for higher levels of the mobilised strength, confer the increment of deformability needed to reproduce the period lengthening due to the plastic response of soil.

3. Application in numerical analyses

The conceptual scheme of the macro-element is illustrated in Figure 3. The soil domain is divided into two parts, namely the far field and the near field [9]. The macro-element is conceived to reproduce the response of the abutment and the soil interacting with it, which constitute the near field where all material and geometric nonlinearities are lumped. The far field refers instead to the area of soil not affected by soil-structure interaction, in which seismic waves propagate under free-field conditions as in the absence of the abutment.

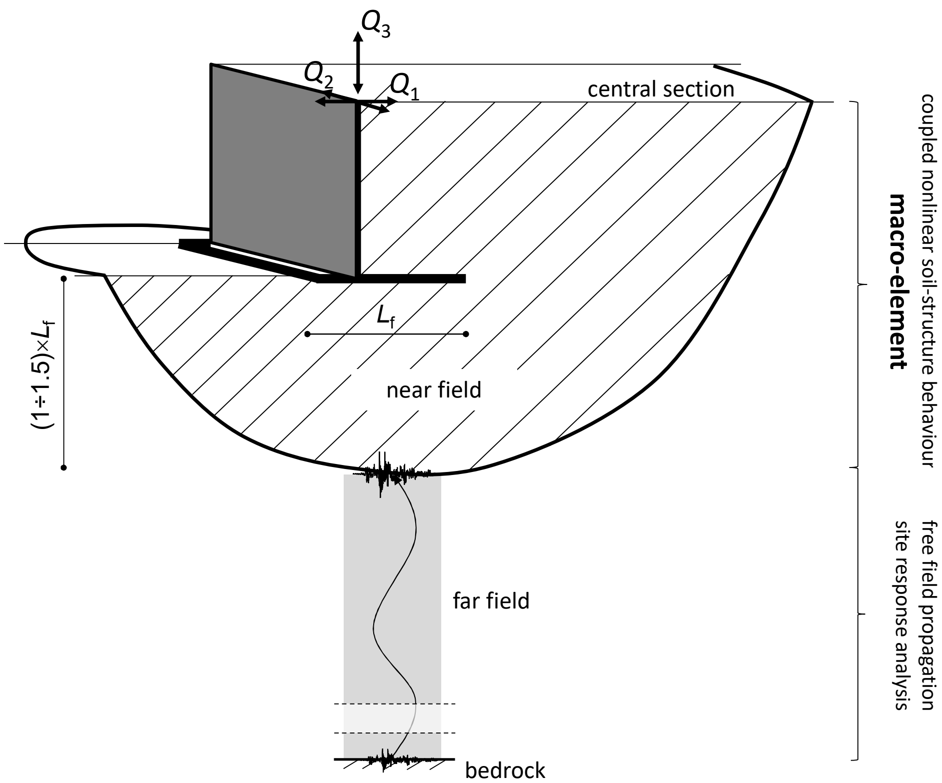

Figure 3. Conceptual scheme of the macro-element modelling.

The principal domain of application of the macro-element consists in carrying out efficient nonlinear dynamic soil-structure analyses in the time domain, in virtue of the drastic reduction of the degrees of freedom of the global structural model accounting for soil-structure interaction. Under seismic conditions, the ground motion coming from the far field is transferred to the superstructure through the macro-element. In this condition, the input motion for the macro-element needs to be characterised by means of time histories of the seismic motion. Within this perspective, the propagation of the seismic waves from the bedrock up to the lower boundary of the near field can be studied through a free-field site response analysis. The free-field seismic motion is then applied to the macro-element to perform a nonlinear time-domain analysis. After evaluating the static or dynamic response of the global structural model accounting for soil-structure interaction, the macro-element response, expressed in terms of force-displacement relationships, can be also used for a prompt evaluation of the stability of the soil-abutment system.

4. Implementation in the OpenSEES framework

The macro-element of bridge abutments was coded in the analysis framework OpenSEES [5,6]: the uni-axial response was initially developed as a new uni-axial material for the OpenSEES library, while the implementation of three-degrees-of-freedom macro-element is currently under development and a concise description of the source code is provided in the following.

4.1 1D macro-element: a new Uni-axial material

The one-dimensional macro-element is susceptible of the rheological representation shown in Figure 4. An elastic spring of stiffness $H^{(0)}$, which the external perturbation is applied to, is connected in series with N sliders characterised by a dissymmetric behaviour (strength in compression $k_+^{(n)}$ different from that in extension $k_-^{(n)}$), that is an essential feature to reproduce the behaviour of bridge abutments. The sliders are the 1D representation of the yield surfaces defined in the general formulation in Section 2.1. The strength parameters increase linearly from the first yield to the ultimate slider, representing the ultimate condition of the system in the direction under examination. Each slider is connected in parallel with a spring of stiffness $H^{(n)}$ that confers kinematic hardening to the response. The n-th dissipative device is provided with a mass $m^{(n)}$ aimed to reproduce the multi-modal response of the soil-abutment system.

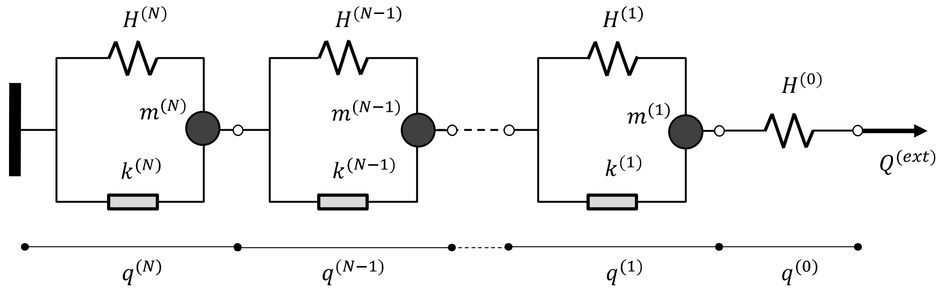

Figure 4. One-dimensional representation of the macro-element for bridge abutments.

The one-dimensional formulation was introduced in the OpenSEES environment as a new uniaxial material that reproduces the response of the fundamental device shown in Figure 5. In this way, the macro-element is regarded as the assembly of N elemental devices, each representing a generalised version of the Kelvin-Voight model with a dissymmetric behaviour and the introduction of a mass. Hence, the elemental device can have a different strength and stiffness in compression and extension.

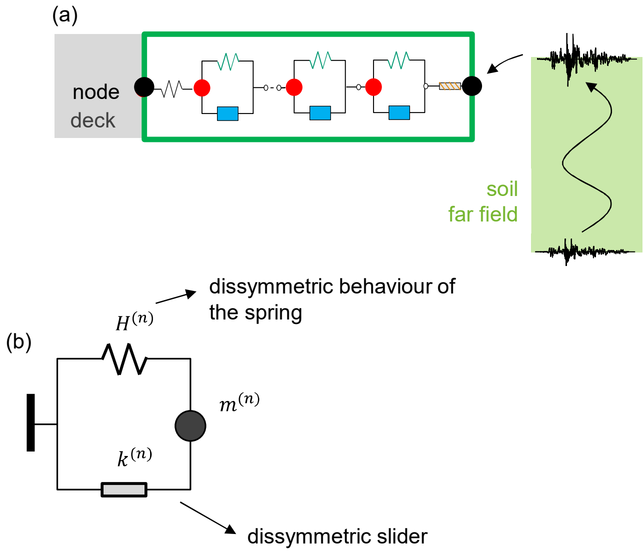

Figure 5. (a) Application of the one-dimensional macro-element in the structural analysis of the bridge; (b) detail of the generalised Kelvin-Voight model implemented in OpenSEES.

4.2 Multi-axial formulation: a new finite element

The multi-axial formulation is implemented in OpenSEES as a new ZeroLength-class finite element, written in the C++ programming language. The source code is composed of two files: a header file (.h), containing the general setting of the model, and a main file (.cpp), in which the model formulation is developed. The input quantities for the source code are the number of yield surfaces and their orientation, the initial stiffness, the ultimate strength and the modal masses of the soil-abutment system. Based on this information, the code generates the entire plastic domain according to the shape of the yield surfaces defined in Section 2.1.

The finite element is composed of two coincident nodes, with three degrees of freedom each, that interact according to the general formulation of the model. The constitutive relations are implemented in incremental form according to the following procedure. The code takes the nodal displacements as the input quantities. The relative displacement between the two nodes is therefore computed and a trial elastic force is determined as the inner product between the relative displacement and the initial elastic stiffness tensor $H_{ii}^{(0)}$. An iterative check on the distance between the trial force and the yield surfaces follows in order to specialise the constitutive relations according to the resistance mobilised. The tangent stiffness matrix is assembled and the effective force vector is finally computed.

5. Calibration

The response of the macro-element can be completely defined by the specification of a limited number of parameters [1,8]. There are some parameters aiming to reproduce the multi-axial force-deformation relationship of the abutment top under monotonic loading conditions. These parameters are the ultimate capacity and the initial stiffness of the soil-abutment system along a reference load direction. The ultimate yield surface can be consequently obtained by the sole information about the bearing capacity of the abutment foundation, starting from which the entire shape and size of the surface can be determined. Similarly, the initial stiffness tensor $H_{ii}^{(0)}$ of the macro-element can be obtained by the initial stiffness of the soil-abutment system in the longitudinal direction (stiffness $H_{11}^{(0)}$ of the macro-element), which can be easily evaluated referring to some experimental and numerical studies [2,10]. Starting from the stiffness $H_{11}^{(0)}$, as a first approximation the same ellipsoidal relationship used for the capacity can be also assumed for the other components $H_{ii}^{(0)}$ of the initial stiffness tensor, that has however a very limited effect on the overall elastic-plastic response due to the small-sized surface of first yield. The dimension of the first yield surface can be reasonably assumed to be equal to 10 % the size of the ultimate locus, as found in [1]. The sizes of the internal yield surfaces can be assumed to vary linearly up to the ultimate yield surface, in correspondence of which the stiffness tensor $H_{ii}^{(N)}$ is taken equal to zero for all its entries. The evaluation of the other stiffness tensors $H_{ii}^{(n)}$ should be associated to the level of mobilised strength for which they are activated and one can refer to the procedure described in [1] for their calibration.

As an example, Figure 6 shows the comparison between the force-deformation curves at the abutment top obtained with the soil-abutment model of the reference bridge system (Section 1) and with the macro-element calibrated following the procedure described above.

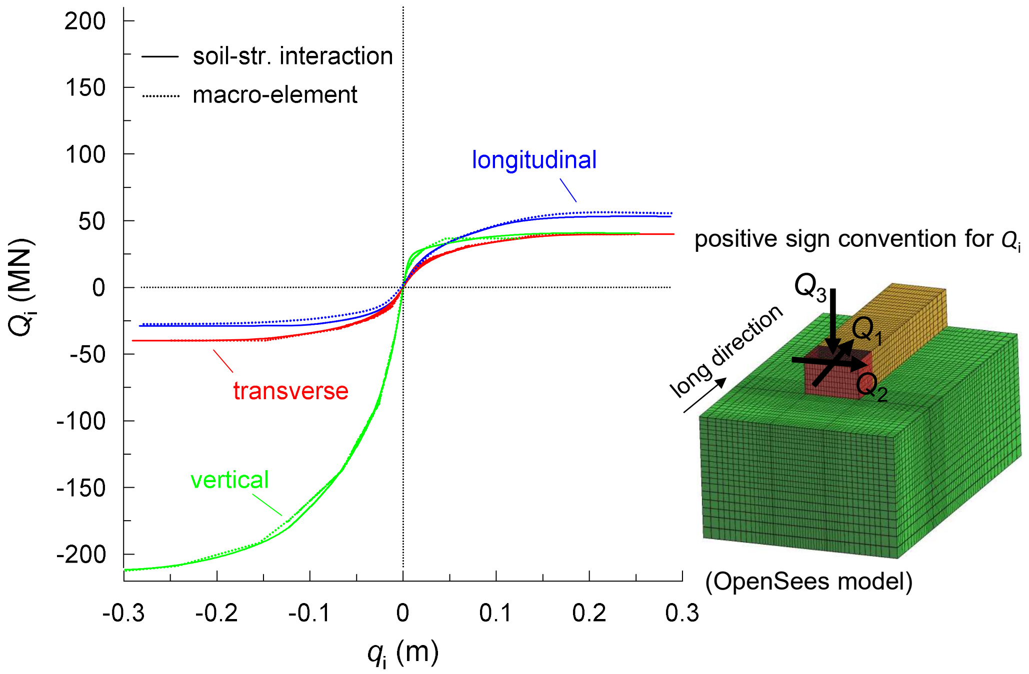

Figure 6. Comparison between the force-deformation curves at the deck-abutment connection obtained with the soil-abutment model (soil-str. interaction) and with the macro-element.

The dynamic properties of the macro-element can be determined by identifying the mass that participates to the dynamic response of the soil-abutment system. As explained in Section 2.2, the frequency-dependent response of the macro-element is mainly controlled by the mass participation $m_{ii}^{(0)}$ of the soil-abutment system at small displacements (reversible response). The latter can be evaluated as $m_{ii}^{(0)}=(T_i^{(0)}/2\pi)^2\times H_{ii}^{(0)}$, as a function of the fundamental vibration period $T_i^{(0)}$ of the abutment and of the initial stiffness $H_{ii}^{(0)}$, regarding the soil-abutment system as a single-degree-of-freedom system [11]. An estimate of the fundamental vibration periods $T_i^{(0)}$ of the system under different directions of motion can be obtained through the analytical solutions provided in [1].

The identification of the masses associated with the higher-order plastic flows requires instead to carry out of a more advanced incremental dynamic analysis of the soil-abutment system in order to analyse the evolution of the elongation period with the level of mobilised strength.

6. Conclusions

Within the context of an analysis method based on macro-elements, the development of an inertial macro-element for bridge abutments can represent an efficient means for a fully nonlinear description of the soil-structure interaction in time-domain dynamic analyses of the entire bridge structure using OpenSEES.

The macro-element is going to be completely included in the OpenSEES framework for a prompt use in multi-component dynamic simulations. The model can be completely identified by a limited number of parameters, which have a clear physical meaning and can be easily obtained from expeditious evaluations. The proposed model allows to take into account the most salient aspects of the soil-abutment interaction, such as a combined nonlinear-inertial response and the marked dependence of the abutment behaviour on the loading direction.

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