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Paper No. 286. *(quote when citing this article)*
Eleventh World Conference on Earthquake Engineering
ISBN: 0 08 042822 3

FLOOR RESPONSE SPECTRA FOR EQUIPMENTS RESTING ON MULTISUPPORT-STRUCTURES

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ABSTRACT

The *effect of the equipment-structure seismic interaction - ESSI* (for "simple" *coupled systems - CS*) was studied, resulting some practical relationships for their *floor response spectra (with E-S interaction) - FRS*, (Olaru and Negoita, 1994). Sometimes, the secondary (sub)systems (which can be equipments/installations- *E*) are connected at various supports (e.g. building structures or different levels of the same structure).This leads to a new concept: *compound floor response spectra - CFRS.* These spectra incorporate the interaction effects between usual ("single") *FRS*'s, when the E's are supported by many primary structures. The theoretical developements and parametrical studies are presented in this paper. Finally, one gives some relationships for the direct evaluation of the earthquake design forces of the secondary systems. These practical formulas (derived from the "simple" form of the *CFRS)* are based on the usual provisions of the national seismic design codes.

KEYWORDS

Compound floor response spectra; design; equipments on multisupports; seismic interaction.

THEORETICAL DEVELOPEMENTS

A relative new direction in the Earthquake Engineering is the study of the seismic behavior and design of the *CS*, (direction denoted here as *DYNACOS*). Some researchers prefered stochastic procedures (Der Kiureghian and Neuenhofer, 1991 - with PSD method), others (Ghobarah and Azis, 1992) studied "simple" cases (E-S as 2 DOF) in the postelastic range, while another investigations (Labbe, 1994) examinated the special case of the ductility demands of the piping systems. But, these investigation programmes neglected the special case of the *CFRS* - a necessary practical approach.

Let consider *one complex equipment/installation - E, supported by many MDOF oscillators.* These supports consist in the "L" level of the "n" structures. The $\mathrm{CFRS}_L(\omega_e)$ will be necessary for the seismic design of the E (sub)systems. Three theoretical formulations resulted for $\mathrm{CFRS}_L(\omega_e)$: *integral form - IF, complex* *form - CF* and "*simple*" *form - SF.*

Integral Form

For equipments supported by MDOF oscillators (structures) at the "L" level, the following relationships of the CFRS were derived:

$$\mathrm{CFRS}_L(\omega_e) = \mathrm{Max}\left|\sum \{A_i^* \int_0^t E_{i,L}(t,\omega_i)\ \exp[-\nu_e\, \omega_e\, (t-\tau)]\ \sin[\omega_i(t-\tau)]\}_i\right| \tag{1}$$

$$E_{i,L}(t,\omega_i) = \sum \{A_{i,L,k}^*\ \ E_{i,k}(t,\omega_{i,k})\}_k \tag{2}$$

$$E_{i,k}(t,\omega_{i,k}) = \omega_{i,k} \int_0^t \{\ddot{y}_g(t)\ \exp[-\nu_{si}\, \omega_{i,k}(t-\tau)]\ \sin[\omega_{i,k}(t-\tau)\, d\tau]\}_i \tag{3}$$

where: A_i^* - participation factor of the "i" support; $A_{i,L,k}^*$ - participation factor of the "i" support, at the "L" level, in the "k" oscillation mode; $\omega_{i,k}$ - eigencircular frequency of the "i" support, in the "k" mode; $\ddot{y}_g(t)$ -ground acceleration; ν_{si} - viscous damping of the "i" structure (for $E_{i,k}$); ν_e - viscous damping of the E-S links (for $E_{i,L}$).

Complex Form

The subsequent relations resulted for the same general case (MDOF supports and multicoupled equipment at the "L" level):

$$\begin{aligned}\mathrm{CFRS}_L(\omega_e) &= \mathrm{Max}\left|\{\sum A_i^* \sum [A_{L,k}^*\ I_{L,k}(\omega_e)\ \beta_{L,k}(\omega_e)]_k\}_i\right| = \\ &= \mathrm{Max}\left|\{\sum A_i^* \sum [A_{L,k}^*\ \ \Phi_{L,k}\ \ddot{y}_g(\omega_e)]_k\}_i\right|\end{aligned} \tag{4}$$

where: $I_{L,k}(\omega_e)$ - input "k" component for the "i" support, for "L" level, at ω_e pulsation; $\beta_{L,k}(\omega_e)$ - amplification function for the "L" DOF (level), in the "k" mode, of the "k" eigenvector, for the "i" support; $\Phi_{L,k}$ - value of the "k" eigenvector, in the "L" DOF (level), for the "i" support.

Simple Form

Let accept - for the representation given in the Fig. 1 - the following notations and characteristics: S_i - primary structures (MDOF oscillators); $k_{e,i}$ - rigidities of the "i" *E-S* links (coupling groups, afferent on "i" primary system); E - secondary system with total mass m_e; i = 1, 2, ..., n. If the ground acceleration is $\ddot{y}_g(t)$, then the "n independent" responses of the secondary system E will be:

$$\ddot{y}_{e,i}(t) = A_{e,i}\ \ \beta_i\ \ddot{y}_g(t) \tag{5}$$

where: $A_{e,i}$ - (over)amplification function of the E; β_i - amplification function for each support "i". But, the important axial rigidity of the E will lead to the following conditions:

$$\ddot{y}_{e,1}(t) = \ddot{y}_{e,2}(t) = \ldots = \ddot{y}_{e,i}(t) = \ldots = \ddot{y}_{e,n}(t) = \ddot{y}_e(t) \tag{6}$$

Consequently, the moderation effect on the $\ddot{y}_e(t)$ will be determined by the mass factors (m_e/m_{si}), with the influence of the so-called *function of the non-simultaneity of the maximum respons oscillations of the primary (sub)systems* - F_n. Finally, the formulas (7),...,(9) resulted.

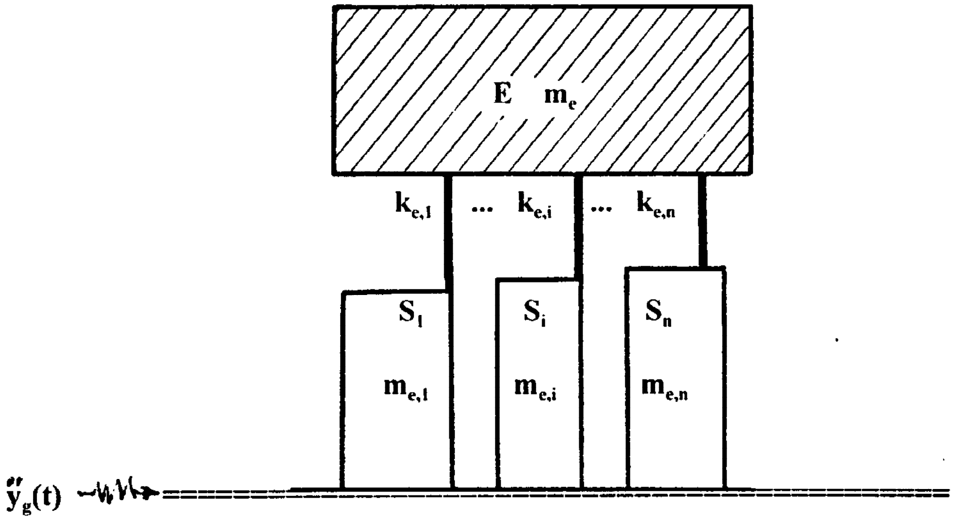


Fig. 1. A secondary SDOF system resting on the multisupport-structures at horizontal seismic actions.

$$CFRS_L(\omega_e) = [F_n/m_e] \sum \{FRS_{L,i}(\omega_e)\, m_{e,i}\}_i \tag{7}$$

$$F_n = \Pi \{[\omega_j/\omega_i] \exp \gamma\}_k \leq 1 , \quad \text{for } i <> j \text{ and } i, j, k = 1, 2, \ldots, n \tag{8}$$

In a first approximation the exponent γ can be considered:

$$\gamma \begin{cases} > 1 , & \text{if } \omega_j < \omega_i \\ = 1 , & \text{if } \omega_j = \omega_i \\ < 1 , & \text{if } \omega_j > \omega_i \end{cases} \tag{9}$$

where: $FRS_{L,i}(\omega_e)$ - floor response spectra of the "L" floor, for the "i" support-structure; $m_{e,i}$ - partial mass of the E, supported by thr "i" primary system; ω_j and ω_i - fundamental circulary frequencies of the "j" and "i" supports.

PARAMETRICAL STUDIES

Idealisation of The E-S Multicoupled Models

A simple coupled system was designed (Fig, 2), in which two primary SDOF structures (S_1 and S_2) support a secondary system (E - working as a rigid body in its horizontal longitudinal axis), connected through 4 links / 2 links for each S_i). On the other hand, the same secondary system E was connected by each primary structure (S_1 - in Fig, 3 and S_2 - in Fig, 4), when the total rigidity of the two links (only) was considered equal with the total rigidity of the four links (from Fig, 2).

The following parameters were varied:

a. the mass ratios: * $m_e/(m_{s1}+m_{s2}) = 0.05; 0.10; 0.20; 0.40$ / * $m_e/m_{s1} = 0.085; 0.17; 0.34; 0.68$ / * $m_e/m_{s2} = 0.117; 0.235; 0.47; 0.94$
b. the relative rigidities of the E-S links - $k_e/k_{s1} = 0.034; 0.075; 0.146; 0.94$
c. the relative rigidities of the S2 support-structure - $k_{s2}/k_{s1} = 0.334; 0.716; 1.36$.

The constant values of the damping ratios were considered $\nu_{s1} = \nu_{s2} = \nu_e = 0.05$.

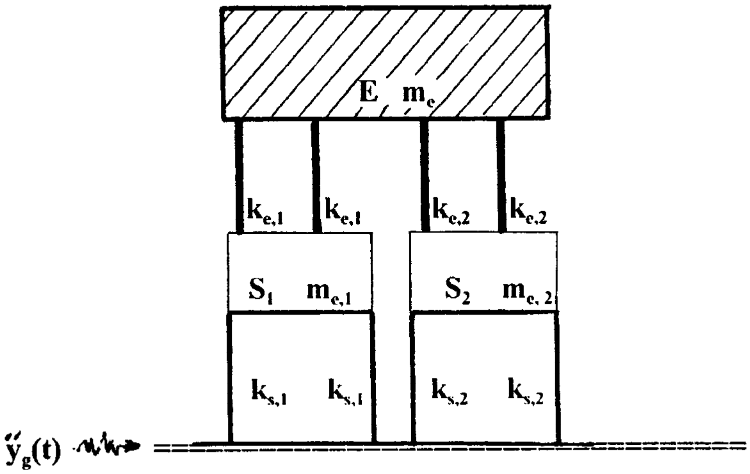


Fig. 2. Coupled system "E resting on 2 different structures" through many connections with various rigidities

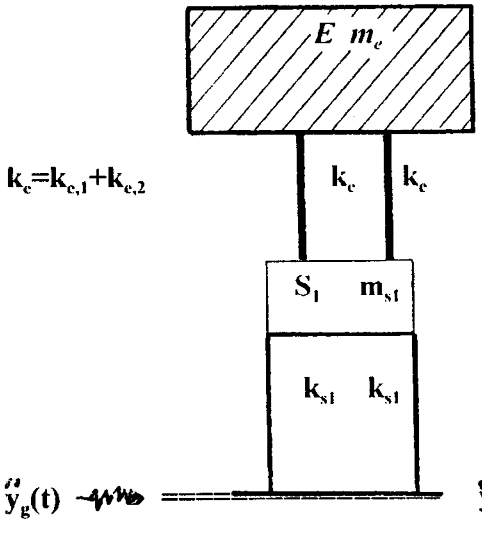


Fig. 3. Simple coupled E by the primary system S_1

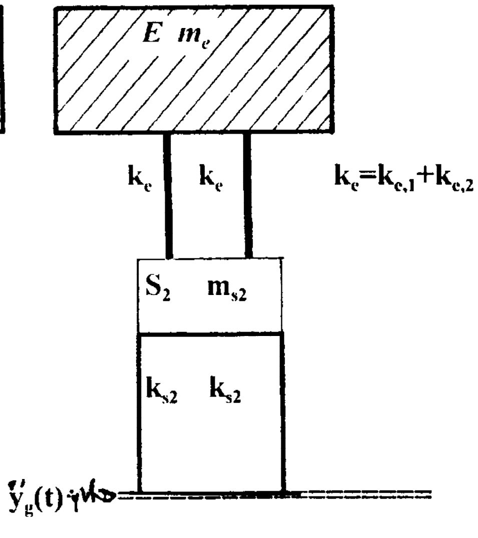


Fig. 4. Simple coupled E by the primary system S_2

Earthquake Actions

Three kind of horizontal artificial earthquakes (*sweep sinous* - *SS* type, which has the constant peak accelerations and variable frequencies) were used: a. with long period - *LP* ($f_{inf} = 0.8$ Hz; $f_{sup} = 1.15$ Hz); b. with medium period - *MP* ($f_{inf} = 1.15$ Hz; $f_{sup} = 1.25$ Hz); c. with short period -*SP* ($f_{inf} = 1.25$ Hz; $f_{sup} = 1.35$ Hz). All excitations had maximum peak acceleration equal with 1 m/s^2, (Fig. 5). These combinations permited to obtain the "tuned" or "nontuned" system-actions dynamic characteristics.

Fig.5. Earthquake SS actions: a. LP; b. SP

Analysis Procedures for Seismic Responses of The First (Complex) System

The time-history analyses were conducted with the programme *PSAP* (FEM method). The main results consisted in the maximum peak accelerations of the E "body" (who is the secondary system) - $a_{e,max}$.

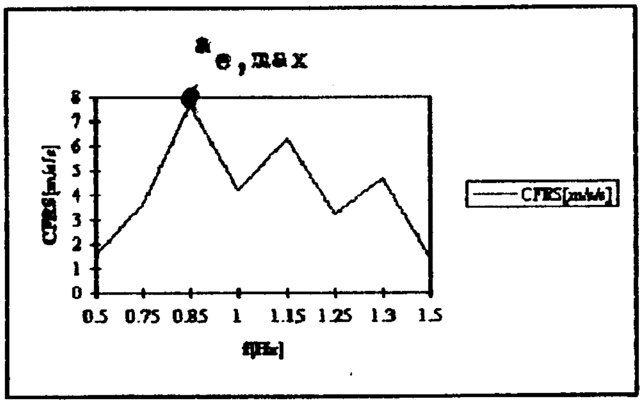
Analysis Procedures for Seismic Responses of The Second (Simple) Systems

Two steps were necessary: a. Time-history analyses (with the programme PSAP); the main results were the response accelerogrames of the support-floors (part of the primary system) - $a_{s,i}(t)$, (i=1 or 2) and the peaks of the response accelerograms of the secondary system - $a_{e,max}$* , also; b. Floor response spectra analyses (with the programme *SPECTREL*) for input accelerograms "$a_{s,i}(t)$", resulting FRS_i , (i=1 or 2).

Verification procedures

Closely values with the $a_{e,max}$ were obtained by combining FRS_1 and FRS_2. A good correlation, confirming the initial assumptions (relations 7,...,9), for exponent γ = -0.85,...,+0.85, has been obtained. An exemple is given in Fig. 6, for the following parameters: $m_e/(m_{s1}+ m_{s2}) = 0.20$, (with $m_e/m_{s1} = 0.34$ and $m_e/m_{s2} = 0.47$); $k_e/k_{s1} = 0.336$; $k_e/k_{s2} = 0.47$.

a.



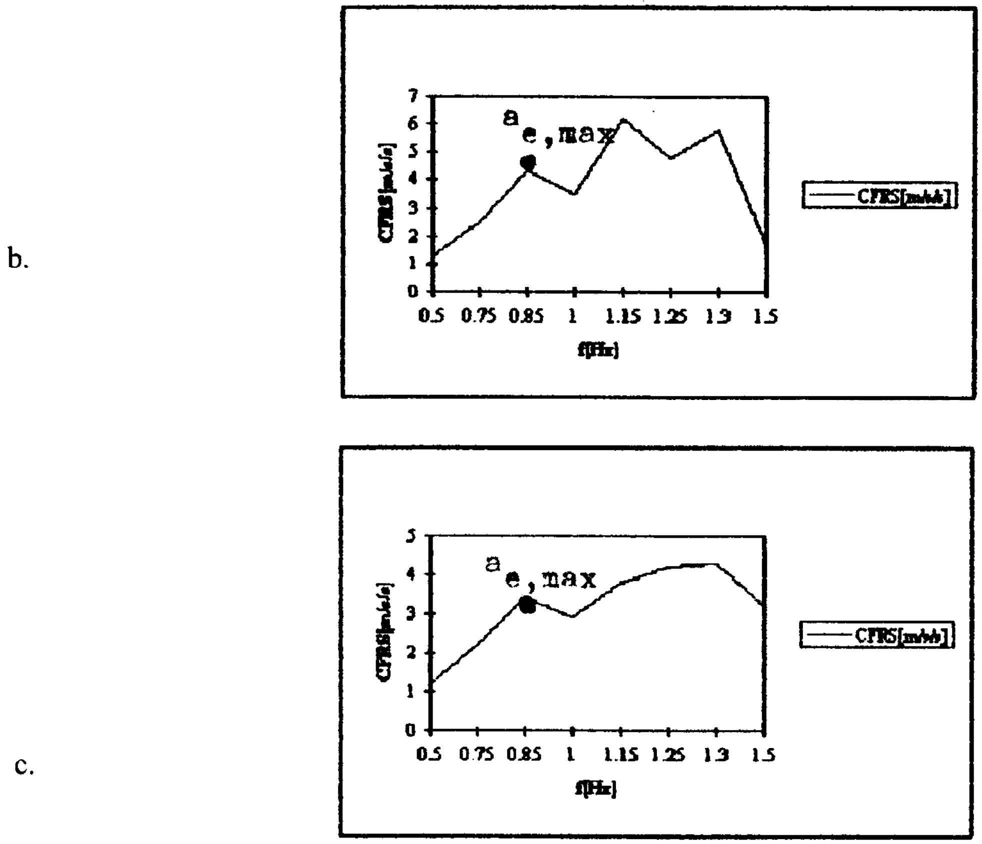
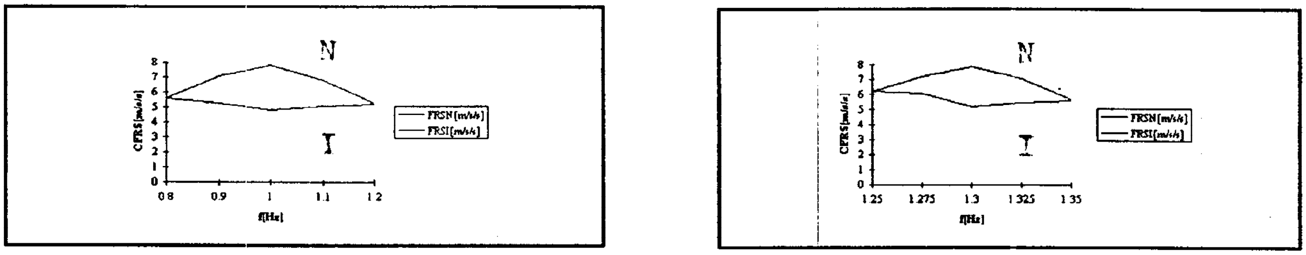


Fig. 6. Comparisons between theoretical $CFRS_l$ and "exact" values of the $a_{e,max}$, for complex E-S system: a. at LP; b. at MP; c. at SP seismic actions

Also, the influence of the ESSI fenomenon is shown by one exemple. One plotted the variance of the FRS with the frequencies for E-S1 system at SP actions (Fig. 7.a) and E-S2 system at LP action (Fig. 7.b). One remarks the "damping effect" in the "tuned" zones only.



a

b.

Fig. 7. ESSI effects over "simple" FRS (N = non-interaction; I = with interaction): a. for S1 at SP actions; b. for S2 at LP seismic actions

CORRELATION RESULTS WITH THE CODE PROVISIONS

Earthquake Design Forces for The Secondary (Sub)Systems Resting on Multisupport-Structures

For the usual systems (E supported by one single structure-support), some practical relations for the evaluation of the earthquake design forces of the equipment - E_e were proved (Olaru and Negoita, 1994). These considerations were extended, now, for the complex systems (E on multisupport-structures). Finally, the following relationships resulted:

$$E_e(\omega_e) = k_s \epsilon_e F_n \sum \{\alpha_{si} [SAF_i(\omega_e)/PCF_i(\omega_e)] \beta_{si} m_{ei}\}_i \text{, with } \Sigma \{m_{ei}\}_i = m_e \tag{10}$$

$$SAF_i(\omega_e) = [k_{si,g} - k_{m,si}] k_{e,si} \tag{11}$$

$$k_{si,g} = \begin{cases} 4.4 \text{, } & \text{if } f_{1,si}/f_{1,g} = 0.8, \dots, 1.25 \\ 4.0 \text{, } & \text{if } f_{1,si}/f_{1,g} < 0.8 \text{ or } > 1.25 \end{cases} \tag{12}$$

$$k_{m,si} = 0.5 [m_e/m_{si}] \tag{13}$$

$$k_{e,si} = \begin{cases} 1.0 \text{, } & \text{if } f_e/f_{si} < 0.5 \\ 1.0 + 0.5 \cos[\Pi \; f_e/f_{si}] \text{, } & \text{if } 0.5 \le f_e/f_{si} < 1.0 \\ 0.3 + 0.2 [f_e/f_{si}] \text{, } & \text{if } 1.0 \le f_e/f_{si} < 2.0 \\ 1.1 \text{, } & \text{if } f_e/f_{si} \ge 2.0 \end{cases} \tag{14}$$

$$PCF_i(\omega_e) = 1 + 1.6 [1 - (1/R_{si})^2 (1/R_e)^2] \tag{15}$$

where: α_{si} - importance factor of the "i" support-structure; $k_s = a_{g,max}/g$ - factor depending on the seismic zonation; ϵ_c - coefficient of the equivalence with 1 DOF for equipment; $SAP_i(\omega_e)$ - supra/over-amplification function of the "i" support; $PCF_i(\omega_e)$ - postelastic correction function of the "i" support; $\beta_{s,i}$ - amplification factor of the "i" support (at the current support-floor); $k_{si,g}$ - function of the (non)tuned structure "i" - ground (predominant frequency); $k_{m,si}$ - function of the mass ratio (e/si); $k_{e,si}$ - function of the (non)tuned equipment-structure "i"; $f_{1,si}$ / $f_{1,e}$ / $f_{1,g}$ - fundamental frequency of the "i" structure / equipment / ground; R_{si} - structure "i" factor ($R_{si} \ge 1.0$); R_e - equipment factor (generally, $R_e = 1$, because equipments "work" in the elastic range). The values of the α_{si}, k_s, β_{si}, R_{si} are given in national seismic codes.

Evaluation of The Earthquake Design Forces of The E-S Couplings

If the equipment "works" as one rigid body its longitudinal axis, then each link/coupling will be acted by following seismic design force:

$$F_{i,L,b} = [k_{l,e,b}/k_{l,e,t}] E_{e,L} \; -/+ \; E_{i,L} \tag{16}$$

where: $F_{i,L,b}$ - seismic design force for "b" link, at the "L" level, with "i" structure; $k_{i,c,b}$ - rigidity of the "b" link, from "c" group, at the "L" level, with "i" structure; $k_{i,c,t}$ - total rigidity of the E-S_i links, at the "L" level; $E_{i,L}$ - proper seismic force of the "L" floor of the "i" support-structure, (the sign - or + takes into account if the oscillations of the two subsystems - primary and secondary - are phased or non-phased).

CONCLUSIONS

The seismic resistant computation of the equipments resting on multisupport-structures includes the following main steps:

a. The evaluation of the function $SAF_i(\omega_e)$, $PCF_i(\omega_e)$ - with relations (11),...,(15), of the $m_{e,i}$ values - as a continous beam and of the code factors (α_{si}, k_{si}, ϵ_e and β_{si}).

b. The determination of the total earthquake force of the multicoupled E on multisupports - with relation (10), (on the basis of the CFRS formulas).

c. The determination of the earthquake forces of each support-floor-structure - with relation (16). If the ESSI fenomenon is insignifiant (after the criteria presented by Olaru and Negoita, 1994), one may make the "isolated" structure seismic analyses; otherwise, the coupled system analyses are necessary.

d. The computation of the "real" forces of the each connection and their verifications (the seismic resistant and displacements).

Further researches are needed in the *DYNACOS* field. Some of these are:

a. The determination of the γ exponent (see formula 9).
b. The evaluation of the spacial CFRS - a general case in the industrial facilities.
c. The influence of the "local" geodynamic conditions.
d. The influence of the type connections.

However, the relations (7),...,(16) can be used in the current aplication, considering the value $F_n = 1.0$.

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