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The state of stress in Spain and its assessment by empirical methods

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ABSTRACT

Methods to assess the in situ stresses have been anasyded through mathematical models and empirical data. An acceptable correlation between the relaxation time function, expressed as the SRF empirical factor, and the K (σ_h/σ_v) values of in situ stresses have been founded. This empirical factor has been applied in Spain where a revision of the available data of the in situ stresses has been carried out.

The direction of the principal stresses determined by fault or focal mechanisms including landsat faultlineations are practicaly the same than those calculated by overcoring techniques.

The K values estimated by SRF are within the same range than those calculated by overcoring. An interpretation on the stress state field of stresses in Spain is also carried out.

INTRODUCTION

The existence of natural stresses and its significance to rock excavations has been well established from the early works of HAST (1967) and VOIGHT (1967), however some of the basic concepts are still under discussion.

According with HYETT et al (1986) the in situ stresses are the result of a complex interaction between four fundamental during mechanism:

- gravitational load
- tectonic forces
- thermal energy variations, and
- physico-chemical processes

From all of these mechanisms the tectonic forces are the dominant at regional scales as indicates by in situ measurements and earthquake focal mechanism. Methods to estimate the in situ stresses are mainly based on the borehole overcoring and hydrofracturing techniques, FAIRHURST, C. (1986). Other methods as the fault analysis allow to determine the direction of the tectonic stress, ANGELIER, J. (1983), RECHES, Z. (1983) and DE VICENTE (1988), or by the earthquake focal mechanism, HATTRI, K (1973) and VASSEUR et al (1983).

During de last 10 years several in situ stress measurements have been carried out in Spain by overcoring and fault or focal mechanisms.

Empirical relationships have been investigated between the main contributing factors to the rock stresses and conceptual mathematical models, in order to find a simple empirical function applicable to regional stress evaluations.

MATHEMATICAL MODEL

Phenomena of building up internal stresses and their consequent evolution along the time, are very complex, varied and difficult to fit in a single and simple mathematical model.

By these reasons, it was tried a group of very simple mathematical models (Fig. 1) and it was attempted to obtain the general structure of stress relaxation laws in order to fit the results of measurements of natural stresses within that structure.

So, we have introduced in the models different constitutive equations for the creep of the rock mass and the geodynamical process. The geodynamical process has been assumed as a prestressed material which is also creeping.

LAMA & VUTUKURI (1978) have given a good and comprehensive review on creep in rocks. The behaviour of rocks in creep is very complex and many models have been proposed for it. Time-dependent deformation of rocks depends upon a number of factors. Some of the most important are the following:

- Nature of stresses
- Level of stresses
- Confining pressure
- Temperature
- Cyclic loading
- Moisture and humidity
- Structural factors

Some of them would be more or less important depending on particular conditions of site.

Two sets of constitutive equations could be differentiated from Vutukuri review: lineal and non-lineal viscoelastic equations.

For lineal ones, it was tried elastic springs and dashpots combined with Maswell & Kelvin units. It has been applied for non-lineal ones the Lomnitz model (1956) after LAMA y VITUKURI (1978).

The resolution of the differential systems provides the laws of stress coefficient, $k = \sigma_h/\sigma_v$, depending on the constitutive equations applied.

For lineal viscoelastic materials, the general structure of relaxation laws obtained from the model can be expressed as follows:

$$k = a + \Sigma b_i e^{-t/\theta_i} \quad (1)$$

Where the parameters a and b_i depend on the viscoelastic constants G_i and η_i, the viscoelastic units and the initial value of coefficient k_0 at time cero ($t=0$).

The parameter θ_i has a dimension of time (relaxation time, quotient of a viscosity by a rigidity modulus).

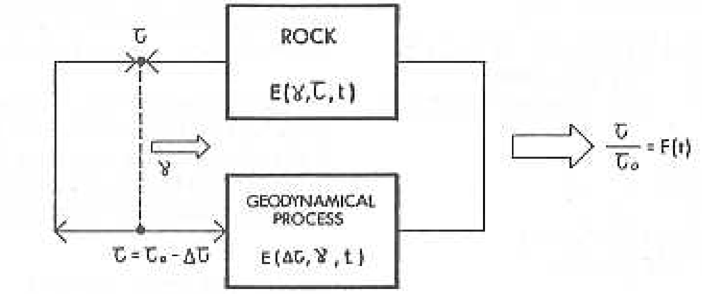

FIG.1.- SCHEMATIC MODEL

For the logarithmic model the relaxation law is an integral equation of the type:

$$K = a + b \cdot \ln(1 + t/\theta) - \int_{0}^{t} \frac{K(s) - 1}{\theta + t - s}\, ds$$

where $\underline{a}$ and $\underline{b}$ are constant and $\underline{\theta}$ is also a relaxation time.

Really, the parameter is a very complicated function within the frame of a thermo-mecanical three-dimensional world, and it is quite illusory to attempt its mathematical expression in so simple way.

Besides the constitutive factors above mentioned, the relaxation parameter depends also on other boundaries conditions such as global tectonic orogeny mechanisms, local neotectonics, geotechnical and geomorphological conditions, actual depth and maximum thickness of the lithostatic column through geological times, temperature evolution, etc.

Due to all these reasons, which are impossible to be included in a simple formulation, it has been choosen a relaxation empirical expression depending on easy to know factors wich seems to fit well to the measurements of in situ stresses.

This empirical relaxation law is a simplification of equation number 2, and seems to fit better to ghe general pattern of internal stress than the ones tried on type 1.

Finally, it has been used a law of the type as follows:

$$k = a - b \log t/\theta \quad (3)$$

The term $\log t/\theta$ it has been called the Stress Relief Factor SRF.

EMPIRICAL ANALYSIS

An empirical analysis between the main factors depending on SRF has been carried out. Only simple and easily available data has been considered. Obviously important simplification have been introduced.

The time factor can be assessed as the time from the main tectonic deformation or orogeny, e.g. Hercynian 300 m.yr. or Alpine 12 m.yr.

The lithostatic load can be estimated as the maximun height of the stratigraphic column overlying the site through geological times. As density of rocks shows small differences over large thickness the lithostatic load can be simplified to the maximun height of the lithostatic column. This height as well as the time from the main orogeny are usually available from regional geological information.

Large topographic anisotropies like deep valley sides or areas within active plate tectonic boundaries have strong influence on the in situ stresses. Two empirical coefficients are introduced to account these effects (SC and NC).

The resulting empirical factor SRF can be expressed as follows:

$$\log \mathrm{SRF} = \frac{T\,(\text{years})}{E(\text{GPa}) \times H(\text{m})} \times NC \times SC$$

where:

T = time from the main tectonic orogeny, in years
E = elastic moduli of rock, in GPa
H = maximun thickness of the lithostatic column through geological times, in metres
NC =neotectonic coefficient with a value of 0,25 empirically obtained, applicable to areas close to large active faulting or active plate boundaries
SC = slope coefficient with a value of 0,30 applicable to areas close to deep valley sides

In cases where both NC and SC are applicable only the 0,25 value must be considered.

SRF has been related to K as a factor depending on the residual stress accordingly with equation 3. The data used to establish the SRF-K relations is included in Table 1. The results are shown in Fig. 2.

Although the number of cases is limited two general trends are observed. One related with the Alpine rocks and other with the Hercynian or Precambrian rocks.

STRESS MEASUREMENTS IN SPAIN

The following methods have been used in Spain to assess the state of stresses:

TABLE 1: IN SITU STRESS MEASUREMENTS

Nº	COUNTRY	EXCAV.	MEASUR.	ROCK	DEPTH	H	T	E	NC	SC	K	SRF	REFERENCE
1	Spain	Mine	O.C.	Lutite	300	3000	300	20	1.00	1.0	1.30	3.69	Campos-84
2	Spain	Mine	O.C.	Shale	200	4000	300	22	1.00	1.0	1.40	3.53	Adaro-84
3	Spain	Mine	O.C.	Granite	400	3000	300	72	1.00	1.0	2.20	3.14	Ramirez-84
4	Spain	Hydroe.	O.C.	Limestone	100	2500	12	10	1.00	1.0	0.80	2.68	Navelón-79
5	Spain	Mine	O.C.	Volcanic tuff	350	2500	300	93	1.00	1.0	2.50	3.11	,Canto-88
6	Spain	Hydroe.	O.C.	Granite	150	3000	300	48	1.00	1.0	1.70	3.31	Ofiteco
7	Austria	Mine	O.C.	Grawacks	750	2500	12	20	1.00	1.0	0.50	2.38	Scheidegger-77
8	Austria	Mine	D.S.	Diabase	10	2000	300	80	1.00	1.0	2.00	3.27	Kohlbeck-80
9	Austria	Mine	O.C.	Sandstone	1100	2000	300	30	1.00	1.0	1.40	3.69	Kohlbeck-80
10	Austria	Mine	O.C.	Limestone	561	2000	300	50	1.00	1.0	1.20	3.47	Kohlbeck-80
11	Austria	Mine	O.C.	Limestone	236	2500	300	40	1.00	1.0	1.40	3.47	Kohlbeck-80
12	Canada	Mine	O.C.	Tuff	600	2000	1000	60	1.00	1.0	1.20	3.92	Herget-73
13	Canada	Mine	O.C.	Quarzite	700	5000	1700	77	1.00	1.0	1.70	3.64	Eisbacher-71
14	Canada	Hydroe.	O.C.	Gneiss	400	7000	1300	80	1.00	1.0	2.20	3.36	Haimson-79
15	Canada	Hydroe.	O.C.	Gneiss	300	4000	1500	50	1.00	1.0	1.70	3.87	Benson-70
16	Canada	Mine	H.F.	Granite	---	9000	1500	75	1.00	1.0	2.90	3.34	Bielenstein-70
17	Italy	Valley	D.S.	Gneiss	210	10000	300	25	1.00	0.3	4.10	2.55	Martinetti-80
18	Italy	Valley	D.S.	Limestone	120	2500	12	56	1.00	1.0	2.00	1.93	Martinetti-80
19	Italy	Valley	D.S.	Dolomite	400	2000	12	56	1.00	1.0	2.50	2.02	Martinetti-80
20	Italy	Valley	D.S.	Limestone	100	1500	12	39	1.00	1.0	0.28	2.31	Martinetti-80
21	Italy	Mine	D.S.	Dolomite	450	1000	12	24	0.25	1.0	2.20	2.09	Del Greco-85
22	Japon	Hydroe.	O.C.	Granite	250	3000	12	18	1.00	1.0	1.77	2.34	Kanagawa-86
23	Japon	Hydroe.	O.C.	Granite	370	3000	12	24	1.00	1.0	1.61	2.22	Kanagawa-86
24	Japon	Hydroe.	O.C.	Granite	71	3000	12	12	1.00	1.0	1.30	2.52	Kanagawa-86
25	U.S.A.	Well	H.F.	Sandstone	1900	2000	12	20	1.00	1.0	1.00	2.47	Haimson-81
26	U.S.A.	Slope	O.C.	Dolomite	50	2000	300	50	1.00	0.3	2.50	2.95	Lee-78
27	U.S.A.	Weel	O.C.	Monzonite	300	2000	12	10	0.25	1.0	2.70	2.17	Zoback-80
28	Australia	Slope	O.C.	Sandstone	30	2000	150	20	1.00	0.3	2.30	3.05	Chappel-84
29	Australia	Mine	O.C.	Shale	380	4000	400	50	1.00	1.0	1.70	3.30	Worotnicki-76
30	U. K.	Hydroe.	O.C.	Shale	100	5000	300	20	1.00	1.0	2.20	3.47	Douglas-83
31	U. K.	Mine	O.C.	Granite	710	3000	300	65	1.00	1.0	2.00	3.18	Pine-83
32	China	Hydroe.	O.C.	Sienito	100	2500	12	60	1.00	0.3	4.00	1.38	Zhu-85
33	India	Hydroe.	O.C.	Gneiss	150	7000	1000	70	1.00	1.0	1.90	3.30	Le Francois-70
34	Israel	Mine	O.C.	Sandst-Dolomit	250	1500	300	6	0.25	1.0	0.26	3.92	Tsur-Lavie-77
35	Norway	Mine	O.C.	Schist	200	5000	1500	50	1.00	1.0	1.90	3.77	Myrvang-76
36	Peru	Hydroe.	O.C.	Andesita	350	1000	12	30	0.25	0.3	1.91	2.00	Price-Jones-84
37	S. Africa	Mine	O.C.	Quarzite	1500	5000	1500	50	1.00	1.0	0.60	3.77	Gay-75
38	Swissz.	Tunnel	D.S.	Gneiss	2500	5000	300	40	1.00	1.0	1.30	3.17	Hast-80

OC - Overcoring
DS - Doorstopper
HF - Hydrofracturing
H - Maximum overburden thickness through geological times (in metres)
T - Age of main tectonic orogeny in million years
E - Elastic moduli of rock in GPa
NC - Neotectonic coefficient
SC - Slope coefficient
K = $\sigma h/\sigma v$
SRF - value of the empirical factor as log SRF

- borehole overcoring (8 sites)
- sample overcoring (1 site)
- population analysis of faults (4 areas)
- population analysis of landsat fault-lineations (2 areas)
- population analysis of focal mechanism (4 areas)

The main data from these measurements are summarised in Table 2 and graphically represented in Fig. 3. From the point of view of the direction of the in situ stresses a good correlation has been founded between the overcoring and the fault or focal mechanism methods, including the landsat fault lineations.

The direction of the principal stresses in Spain is shown in Fig. 4.

The present stress field indicates a main compressive stress aproximatly Nort-South (NNW-SSE), as a result of the present tectonic thrust between the African and the Euroasian plates, and a main tension stress approximately East-West (EEN-WWS) direction. These regional directions can be changed due to local tectonic anisotropies (Fig. 4).

According with Fig. 2 the Hercynian rocks are better represented than the Alpine rocks where only one case of in situ measurement is available in Spain. The best fit line for the Hercynian rocks (Fig. 2) is:

$$\log \mathrm{SRF} = 0.34k + 4.03$$

The results of K assessed by SRF and the direction of the stresses are showed in Table 3. The obtained values of K are in the same range than those measured by overcoring techniques. The direction of the principal horizontal stress estimated by fault or focal mechanisms methods are in a very good agreement with the overcoring techniques.

DISCUSSION AND CONCLUSIONS

Phenomena of building up internal stresses and their release with time are complex and difficult to fit in a single and simple mathematical model. By these reasons very simple mathematical formulations have been analysed. The available empirical data indicate that the non-lineal logarithm viscoelastic behaviour fits better than the lineal viscoelastic. For the analysed empirical data the best fit is founded when the relaxation time ( ) is proportional to the product of the elastic modulus by the maximun thickness of overlying materials, corrected by two coefficients to account for neotectonic and geomorphological conditions.

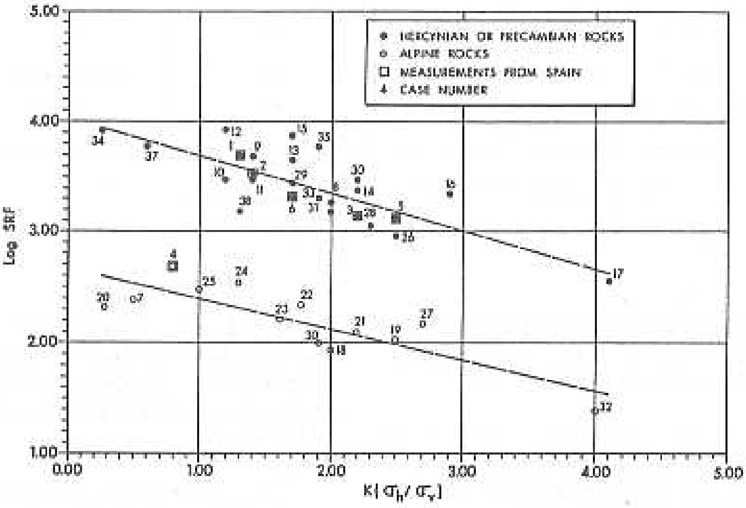

FIG. 2 .- EMPIRICAL RELATIONSHIP OF K AND SRF

TABLE 2: STRESS MEASUREMENTS IN SPAIN

LOCALITY Nº	FACILITY	METHOD OF MEASUREMENT	ROCK	DEPTH (m.)	E GPa	K $\sigma H/\sigma V$	DIRECTION σH	REFERENCE
1 Peñarroya - C. Real	Mine	BOC	Lutite	300	20	1.30	114	CAMPOS, A. 1984
2 Valdeorras - Orense	Mine	BOC	Shales	200	22	1.40	47	E.N.ADARO, 1984
3 Linares - Jaén	Mine	BOC	Granites	415	72	2.20	85	RAMIREZ, O. et al, 1984
4 Cortes - Valencia	Cavern	BOC	Limestones	100	10	0.80	170	NAVALON et al, 1979
5 Sotiel - Huelva	Mine	BOC	Volcan. tuffs	350	93	2.50	180	CANTO. J.M., 1988
6 Sallente - Lérida	Cavern	BOC	Granites	150	48	1.70	154	OFITECO, 1988
7 Aldeadávila - Salamanc	Cavern	BOC	Granites	379	27	n.r.	151	OFITECO, 1988
8 Saucelle - Salamanca	Cavern	BOC	Granites	65	25	n.r.	163	OFITECO, 1988
9 Pajares - León	Tunnel	SOC	Limestones	Surface	30	n.a.	180	E.N.ADARO, 1982
10 Tous - Valencia	Dam	FA	---	---	---	---	170	PROSPECCION E ING., 1986
11 Pirineos - Navarra	Tectonic inv.	EFM	---	---	---	---	145	CAPOTE, et al, 1988
12 Pirineos - Huesca	Tectonic inv.	EFM	---	---	---	---	154	CAPOTE, et al, 1988
13 Granada	Tectonic inv.	EFM	---	---	---	---	162	DE VICENTE, et al, 1987
14 Sierra - Madrid	Tectonic inv.	FA	---	---	---	---	172	DE VICENTE, et al, 1987
15 Alboran	Tectonic inv.	EFM	---	---	---	---	150	DE VICENTE, et al, 1987
16 Andujar - Jaén	Radiact. wastes	FA	---	---	---	---	80	PROSPECCION E ING., 1987
17 Siguenza - Guadalajara	Tectonic inv.	FA	---	---	---	---	165	DE VICENTE, 1988
18 Galicia	Radiact. wastes	LFA	---	---	---	---	180	CAPOTE, et al, 1989
19 Zamora	Radiact. wastes	LFA	---	---	---	---	170	CAPOTE, et al, 1989
20 Avila	Radiact. wastes	LFA	---	---	---	---	165	CAPOTE, et al, 1989

BOC: Borehole overcoring; SOC: Sample overcoring; FA: Fault analysis; EFM: Focal mechanism; LFA: Landsat fault analysis
Direction in degrees
n.r.: no representative; n.a.: no aplicable

TABLE 3.-K VALUES AND DIRECTION OF PRINCIPAL STRESSES IN SPAIN

SITE	K FROM IN SITU MEASUREMENTS	K FROM SRF BEST FIT LINE	DIRECTION OF σ_H FROM IN SITU MEASUREMENTS	DIRECTION OF σ_H FROM FAULT/FOCAL MECHANISM
1 Mine	1.30	1.00	114	No available
2 Mine	1.40	1.47	47	No available
3 Mine	2.20	2.61	85	80
4 Cavern	0.80	0.04 * 0.95 **	170	170
5 Mine	2.50	2.70	180	No available
6 Cavern	1.70	2.11	154	154

* Mean value for the best fit line
** Mean value for the fit line at 95% conficence limit

The resulting empirical factor SRF has been related with actual values of K. An acceptable correlation of SRF-K have been founded.

The analysis of in situ stress carried out in Spain by different methods has shown that the direction of the principal stresses can be determined by fault, landsat fault-lineations or focal mechanisms. The directions obtained by these methods are the same than those measured by overcoring techniques.

The K values predicted by SRF and those measured by overcoring, for the Hercynian rocks in Spain, are within the same range of values. No representative values are still available for the Alpine rocks.

The interpretations of the stress field are in accordance with the present plate tectonic activity of the Iberian Peninsula, with a main compresive stress almost north to south due to the African and Euroasiatic thrust, and a main tension stress almost east to west direction.

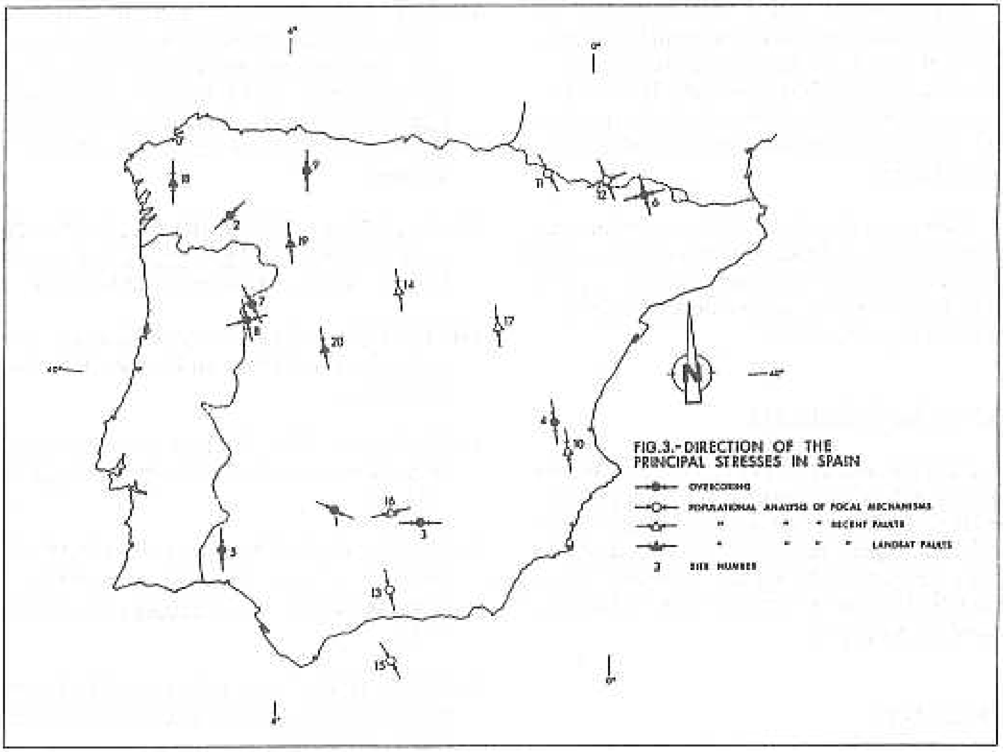

FIG.3.- DIRECTION OF THE PRINCIPAL STRESSES IN SPAIN

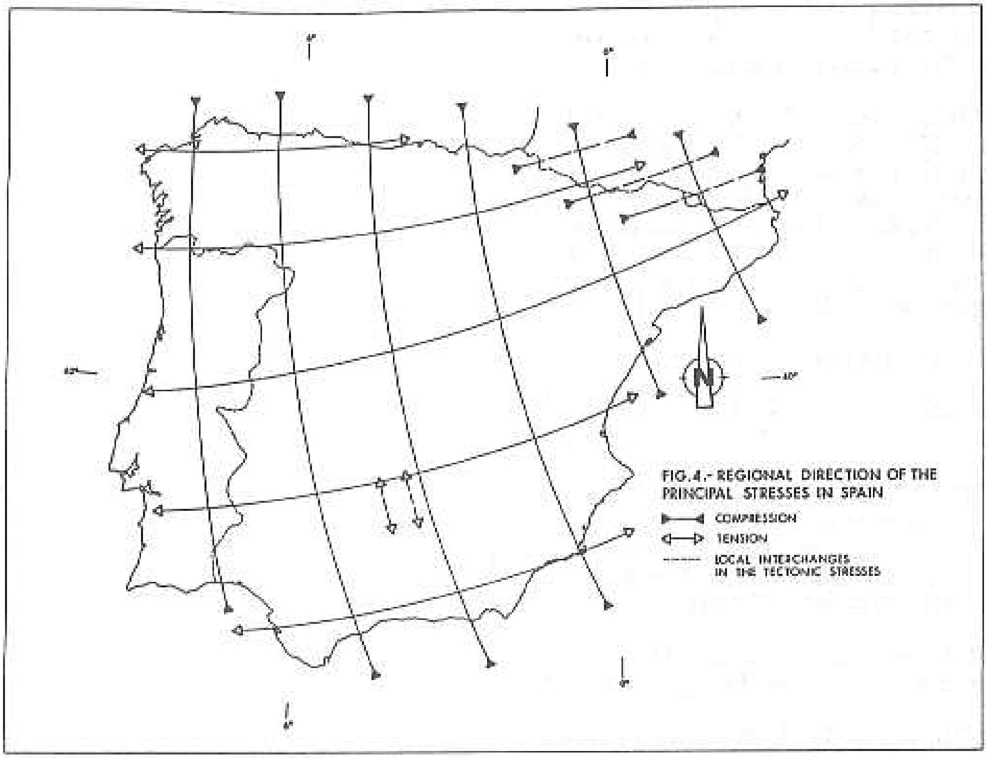

FIG.4.- REGIONAL DIRECTION OF THE PRINCIPAL STRESSES IN SPAIN

The empirical SRF factor as well as the fault/focal mecanisms methods could be alternative procedures to estimate the in situ stresses before in situ testing is carried out. These systems are simple to applied and can be used as complementary of the overcoring or hydrofracturing techniques.

Relevant advantages of these methods can be obtained during the early stages of underground excavation design where major problems derived from high in situ stress and the best excavation axis should be recognised.

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