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15. *Optimum Distribution of Seismic Observation Points. IV*

— Desirable Location of a New Station in Yugoslavia —

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Abstract

The problem of optimum distribution of seismic observation points here discussed is what will be the best location for the new station which is to be set up in addition to the present ones in Yugoslavia. An epicenter was assumed and then the errthquake parameters were calculated using the data of arrival times of the present eight stations which are not without a certain amount of observation errors. If the observation error is normally distributed and has a standard deviation 0.1 sec the average value of the expected errors for the epicenter location and the origin time are about 3.1 km and 0.77 sec respectively. Then a new station and its location was changed uniformly with a constant stepping within the territory of Yugoslavia. If an adequate location is chosen for the additional station, the average values of expected errors all over the country decrease as much as 20%. In this way the optimum location of the new station was discussed, the calculation being based on the Monte Carlo method.

1. Introduction

Geologically speaking, Yugoslavia belongs to the Alpine Belt and in the course of her history she experienced a number of very strong earthquakes. At the moment seven seismic stations are being operated and the eighth is now under construction. If we consider the seismic activities of the area of about 256,000 km^2 and the population inhabited there, eight stations are not sufficient and it is now seriously considered advisable to add a new seismic station with high magnification instruments.

In this paper the problem of the optimum location of this new station is discussed. The method used by the present authors[2)] is similar to that originated by E. Herrin.[1)] E. A. Flinn also gives a way of attacking the precision problem, which is more theoretical.[3)]

2. Fundamental formulas and assumptions

The equation for the errors of epicentral location, depth, arrival time and propagation velocity is:

$$\begin{aligned}(X_j - X_0 - x)^2 + (Y_j - Y_0 - y)^2 + (H + h)^2 \\ = (V + v)^2 \cdot (T_j + e_j + t)^2 \qquad (j = 1, 2, \cdots),\end{aligned} \tag{1}$$

where j index number of each station
X_j, Y_j coordinates of seismic stations
X_0, Y_0 coordinates of epicenter
H depth of focus
V propagation velocity of waves
T_j travel time
e_j observation error of arrival time
x, y, h, t, v errors of the location of focus, origin time and the velocity, which result from calculation.

The following assumptions were adopted as before

i)—the errors $x, \cdots, v$ are small,
ii)—stations are on a flat surface,
iii)—velocity of elastic waves is constant
and iv)—observational errors e_j follow Gaussian distribution with mean value 0.

1) E. HERRIN, "Errors in Epicenter Locations," *Symposium of Geophysical Theory and Computers*, Moscow, June 1963.

2) Y. SATÔ, "Optimum Distribution of Seismic Observation Points," *Zisin*, [ii] **18** (1965), 9. (In Japanese)

Y. SATÔ, and D. SKOKO, "Optimum Distribution of Seismic Observation Points," *Bull. Earthq. Res. Inst.*, **43** (1965), 451.

D. SKOKO, Y. SATÔ, I. OCHI and T. K. DUTTA, "Accuracy of the Determination of Earthquake Source Parameters as Determined by Monte Carlo Method. Observation on Indian Network," *Bull. Earthq. Res. Inst.*, **44** (1966), 46.

3) E. A. FLINN, "Confidence Regions and Error Determinations for Seismic Event Location," *Rev. of Geophys.*, **3** (1965), 157.

Since the area in question is of no large size, geographical coordinates were transformed into Cartesian coordinates with the origin at the center of the region and the axes x(eastward), y(northward) and z(downward). The x and y coordinates of a point (α, β) referred to the center of the region (α_0, β_0) were given as follows:

$$x = 1.8584\,(\beta - \beta_0)\cos((\alpha + \alpha_0)/2) \qquad (2)$$
$$y = 1.8519\,(\alpha - \alpha_0)$$
$$(\alpha, \alpha_0, \beta, \beta_0 \text{ in min.})$$

3. Present observation in Yugoslavia

Yugoslavia is not a large country with the dimension about (800 km $\times$ 500 km), the present eight seismic stations being listed and illustrated below. Errors were allotted to each of these stations from a random number series and the equation (1) was solved using the least square method for a certain epicenter location. A similar calculation was repeated 300 times for the same origin location and the standard deviation

Table 1. Seismic stations in Yugoslavia

Station		Latitude (North) deg min	Longitude (East) deg min	Instrument
1	Ljubljana	46 02.6	14 32.0	1) Wiechert Mechanical 200 kg. Horizontal 2) Hiller Optical Vertical
2	Zagreb	45 49	15 59	1) Wiechert Mechanical 1000 kg. Horizontal 2) Id. 1300 kg. Vertical 3) Id. 80 kg. Horizontal
3	Sarajevo	43 52.4	18 25.7	1) Mainka Mechanical 450 kg. Horizontal
4	Beograd	44 49.3	20 27.3	1) Wiechert Mechanical 1000 kg. Horizontal 2) Id. 1300 kg. Vertical
5	Titograd	42 25.8	19 15.6	1) Mainka Mechanical 450 kg. Horizontal
6	Skopje	41 58.3	21 26.4	1) Lehner-Griffth Short Period 2) Press-Ewing Long Period 3) Wilmore Short Period 4) Strong Motion Recorder 5) Mainka Mechanical 450 kg. Horizontal
7	Ohrid*	41 08.0	20 50.4	1) Lehner-Griffth Short Period
8	Valandovo	41 20.2	22 35.3	1) Lehner-Griffth Short Period

* Under Construction

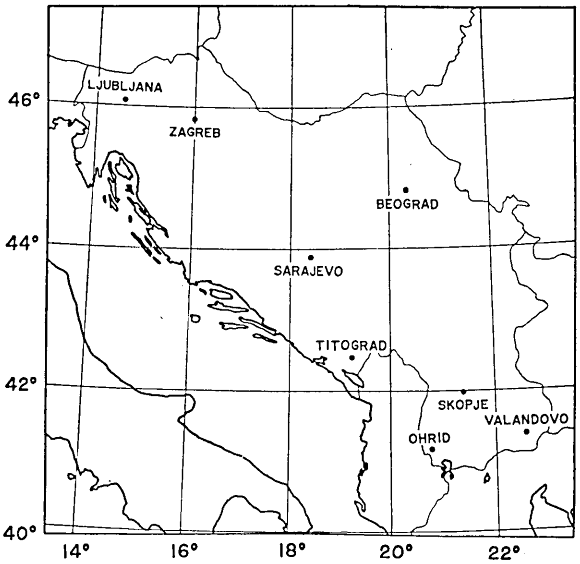

Fig. 1. Distribution of seismic stations in Yugoslavia

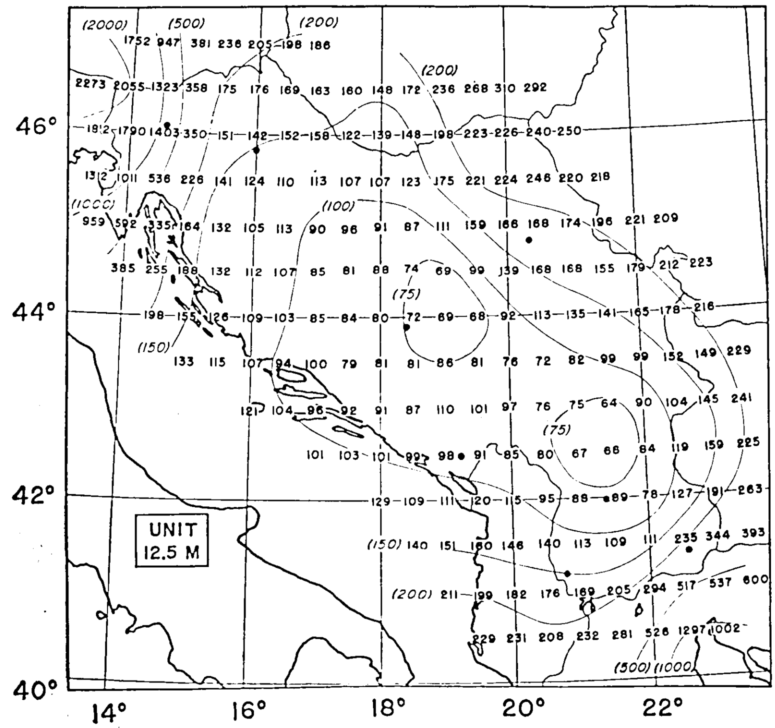

Fig. 2. Distribution of ΔR (error of epicenter location) when there are only 8 stations given in Table 1. Unit of length is 12.5 m, therefore the smallest value in the figure is 0.8 km and the average about 3.1 km.

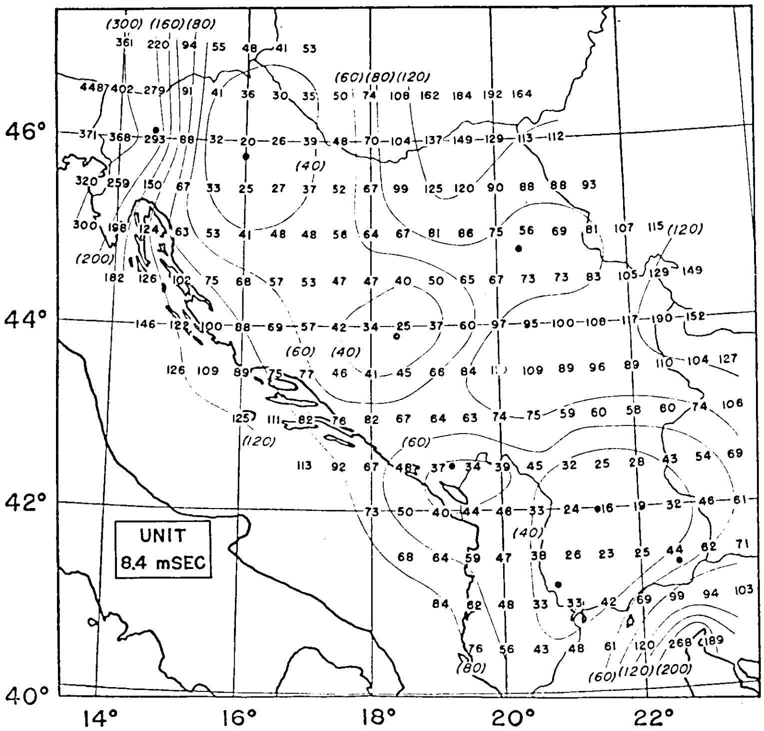

Fig. 3. Distribution of ΔT (error of origin time) when there are only 8 stations given in Table 1. Unit of time is about 8.4 msec, therefore the smallest value in the figure is 0.13 sec and the average about 0.77 sec.

was calculated for r, h, t and v. (r is the vectorial sum of the errors x and y.) The numerical assumptions in this calculation are:

Standard deviation of the errors e_j = 0.1 sec.
Depth of the focus = 25 km.
Wave velocity = 7 km/sec.

The epicenters were placed at intervals of 30′ both in longitude (about 40 km) and in latitude (about 55 km); altogether there were 200 cases.

The accuracy of the observation at the present condition thus elucidated is given in Figures 2 and 3. According to the calculation based on the Monte Carlo method the errors are small in the central part of the country and large at the boundary. The smallest and average values are, translating into ordinary units, about

	ΔR	ΔT
Minimum	0.8 km	0.13 sec
Average	3.1 km	0.77 sec

4. Additional New Station

In order to make clear the problem of where the most desirable location of a future station should be, 84 points were taken all over the territory with intervals of 1° in longitude (80 km) and 30′ in latitude (about 55 km), and for each of this new position similar calculation of error estimation was done as in the previous section.

The criterion of the "Suitability" of the new station is "How small the observation errors will become when that specific station is added." In the present section, therefore, the distribution of the errors

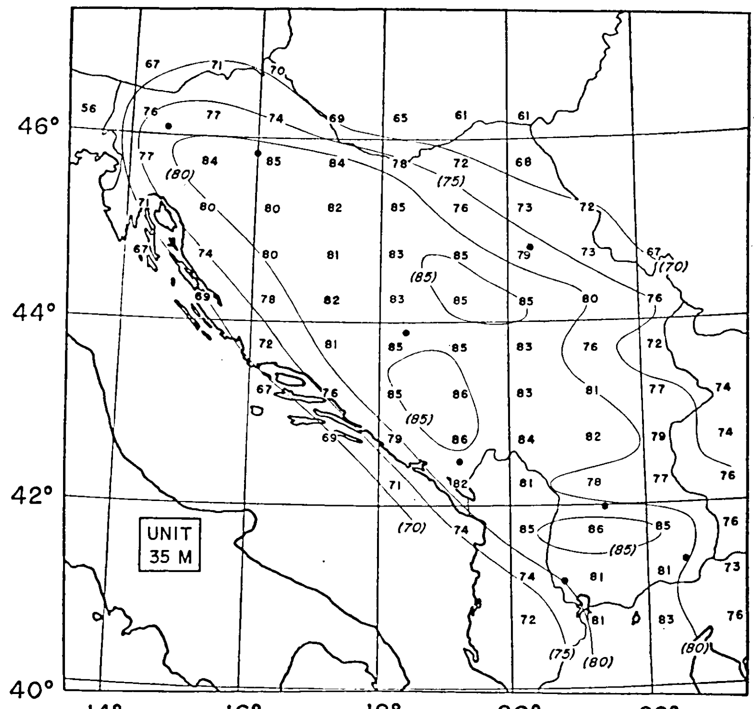

Fig. 4. Mean value of ΔR when an extra station is added. Mean ΔR is given as the function of the new station location. The unit of length is 35 m, therefore the contour of (85) implies the curve of $\Delta R \doteqdot 3$ km.

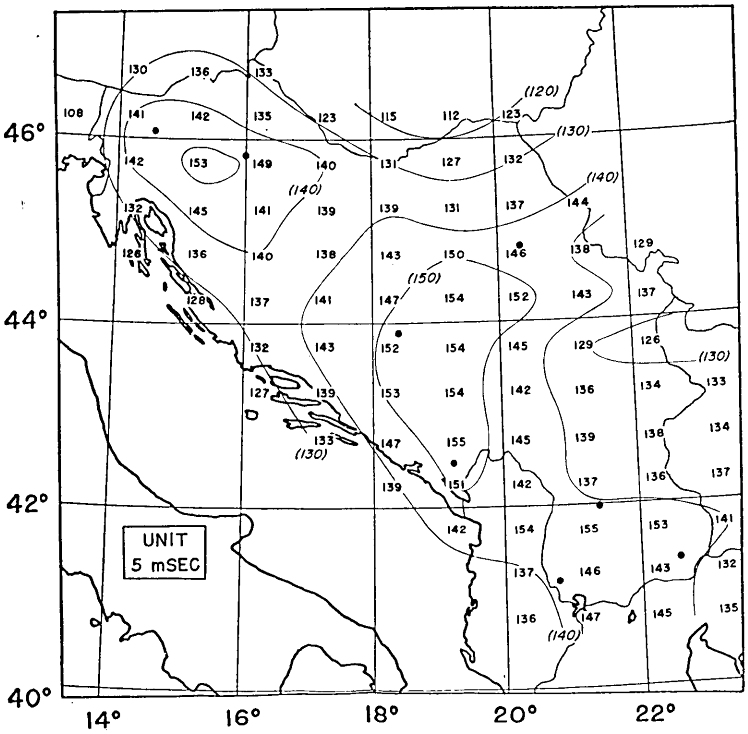

Fig. 5. Mean value of ΔT when an extra station is added. Mean ΔT is given as the function of the new station location. The unit of time is 5 msec, therefore the contour of (140) implies the curve of $\Delta T = 0.7$ sec.

at 200 epicenters is not discussed in detail, but the mean value of those expected values as a function of the new station location is studied. The trial calculations were repeated about 80 times for each extra station. In this way the calculated values of mean square errors were plotted in the map.

As is seen in the last line of the previous section the mean values when only the present eight stations are available are $\Delta R = 3.1$ km, $\Delta T = 0.77$ sec, while the smaller values found in Figures 4 and 5 are (translating into ordinary units) about

$$\Delta R = 3.0 \text{ km}, \qquad \Delta T = 0.75 \text{ sec} .$$

Consequently the construction of an additional station scarcely brings an accuracy improvement if it is situated in the central part of the country. If, however, a good place is chosen, the average improvement amounts to as much as 20%. (In Figures 4 and 5 compare the largest and smallest values, which are 20% smaller than the former.)

5. Conclusion

Distribution of the existing network of seismic stations in Yugoslavia is rather satisfactory. It enables us to calculate earthquake parameters with a pretty good accuracy in most part of the territory. The weak points, however, lie in the circumferential region. If we compare Figures 2 and 3 with Figures 4 and 5 respectively, we can see that the regions with bad precision harmonize with the regions favorable for a new set-up. The above mathematical study gives a clue, even without Figs. 4 and 5, where the new stations should be constructed. We should, however, add another geophysical fact of practical importance. Very roughly speaking, the seismic activity in Yugoslavia increases from north-east to south-west the seismicity reaching its maximum in north-west and south-east regions of the country, as well as along the coastal area of the Adriatic Sea. There are, however, isolated inland

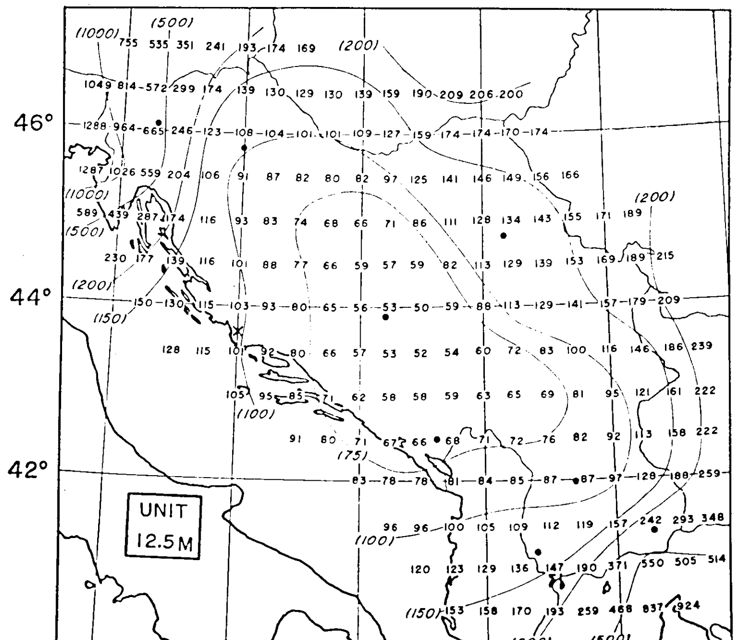

Fig. 6. Distribution of ΔR when the 9th station was set up at 43°45′N, 16°00′E. (Compare with Fig. 2.)

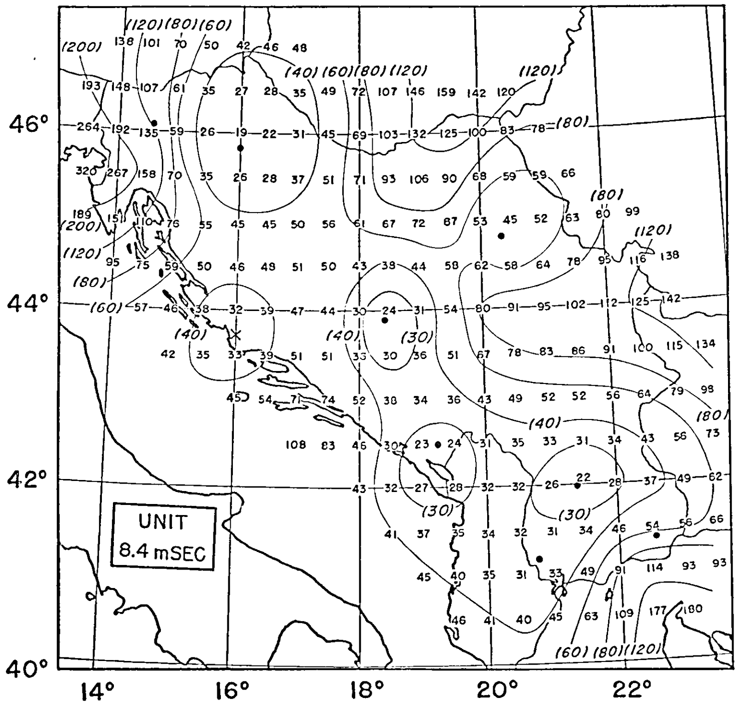

Fig. 7. Distribution of ΔT when the 9th station was set up at 43°45′N, 16°00′E. (Compare with Fig. 3.)

regions such as the areas around (44°N, 21°E) and (45.5°N, 18.5°E) where the seismicity is comparatively high.

Taking into account the above facts we can draw a conclusion that the spots recommendable for setting up a new station in Yugoslavia are at first the territory along the coast of the Adriatic Sea and second the region around the point (43.5°N, 21.0°E). From Figs. 4 and 5 we recognize that both these regions make the mean value of the error small. As an example a new station was assumed at 43°45′N, 16°00′E and ΔR (Fig. 6) and ΔT (Fig. 7) were calculated. It will be interesting to compare these figures with Figs. 2 and 3.

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15. 地震観測点の最良分布 IV

ユーゴスラヴィア新観測所の最適地

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ユーゴスラヴィアには現在8個の地震観測所があるが（第1表および第1図参照），さらに新しく一つの観測所を建設しようとの計画がある．その位置をどこにとつたならもつとも有効であるか，という問題を，以前からとつていると同様のシミュレイションの方法によつて考えてみた．

そのための順序として，まず，現存する8個の観測点のみによる時，震央位置および発震時の誤差（ΔR, ΔT）がどのようになるかをしらべた．考える震央位置としては，経緯度とも30分おきで，ユーゴスラヴィア全土を覆う200の点をとり，ここに地震が起こつた時に期待される誤差を最小二乗法によつて計算し，さらにこうした操作を250回くり返して，正確な ΔR および ΔT の算出につとめた．結果は第2，第3図に示す通りで，

	ΔR	ΔT
最小値	0.8 km	0.13 秒
平均値	3.1 km	0.77 秒

の程度となる．ただし計算は次のような仮定のもとに行なわれた．

1) 各観測点での誤差は正規分布をなす
2) その平均値は 0，標準偏差は 0.1 秒
3) 震源の深さは 25 km
4) 媒質は一様で波の速度は 7 km/秒
5) 観測点は同一平均面にある．

次に1個の観測点を加え，9個所での観測を用いて上と同様の方法で ΔR, ΔT を求めた．この場合には，誤差に対する震央位置の影響をこまかくは論ぜず，200の震央についての平均値を求め，これを新観測所の位置の関数と考えた．このように考える時，求められた平均値の小さいのが，望ましい新観測所の建設地点となるわけである．緯度30′おき，経度1°おきの84点について行なつた計算結果は第4，第5図となる．もともと観測精度のよい国の中央部には，新しい観測所を加えても ΔR =3.0 km, ΔT=0.75 sec 程度となつて，全体としての精度の向上はあまり望めない．これに反して適当な点をえらぶならば，平均で20%くらいの精度向上を期待し得ることになる．

一例として，第4，第5図からみても適当と思われ，地震も少なくないアドリア海沿岸の一点（43°45′N, 16°00′E）に新観測点を設けた時の ΔR および ΔT の分布を第6，第7図に示す．それぞれ第2，第3図とくらべる時，観測点の追加がどんな影響をもつかがわかつて興味ぶかいことと思う．
