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FINITE ELEMENT MODELLING OF THE SEDIMENTARY BASIN WITH THRUST STRUCTURES

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Using computer modelling on the basis of the 2-D finite-element method, the dynamic conditions of tectonic compression of sedimentary layers are investigated. These models represent a geotectonic situation for the Ukrainian Carpathians in Early Cretaceous time taking into account a simplified cross-section. Geometrically, this cross-section include three parts: moving thrust wedge, layered sedimentary complex and fixed declined basement of the continental platform. Series of genetically inherited models, in which the number of thrust faults increases, are constructed. The detailed numerical models within the framework of continuum mechanics are used: the finite-element resolution is 500x100 m with biquadrate approximation of displacements. The stress-strain state in the non-homogeneous medium with essentially non-uniform mechanical properties according to flysch composition of load-bearing and weak layers with different thicknesses are studied. Linear range of the models: total thickness – up to 5 km (included 1 km as water hydrostatic pressure) and 50–80 km in lateral direction. The non-ideal contact with slipping between layers and stress relaxation are taken into account.

The analysis of computer modelling results and investigation of the stress-strain state is carried out on the several 2D-models, presented by cross-sections, for which hypotheses of plane deformation in the gravitational field are accepted. Results of modelling displayed some deformation features and stress distribution during compression up to 2.5 km. "Snapshot" maps of stress and strain fields according to thrust wedge moving by step 0.5 km are constructed. Particular attention is given to the area of tee-like contact between front and back rock massifs regarding the faults of thrust kids and base layers at the detachment horizon.

The occurrence of laterally periodic zones of high stress level control (on the basis of the brittle-fracture criterion) the formation and development of slightly sloping faults through sedimentary layers. Plastic strains for lower layers on the detachment horizon by long-time creep are modelled. Near to the faults they are accumulated and resulted in folded structures, but ones are practically absent in the apical parts of thrust block.

Self-consistent restructuring of models that track the origin and evolution of thrusts or take into account 3D-inhomogenity can be a task for future research.

Key words: computer modelling, the finite element method, thrust structures, the stress-strain state, layered medium.

Tectonic cover nappes are typical structural units for many active belts which have passed a convergent development stage. They are available in the Alps, Carpathians, Scandinavian Caledonides, Canadian Rocky Mountains, Urals Mountains and other sites of the Earth’s crust.

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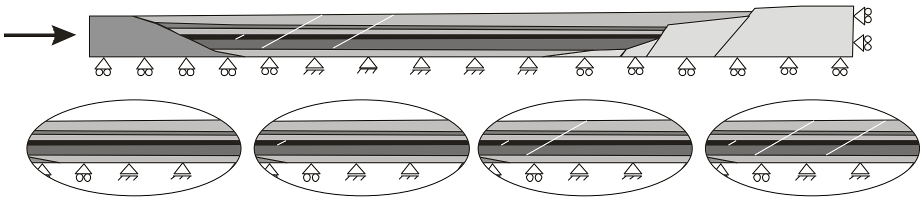
By object of research it is chosen covers of the Ukrainian sector of the Carpathians. The mechanism of formation and dynamic conditions of their becoming is important for explanation of such geological structures and remain open to question [2, 3, 5, 6]. The modern structures are result of mainly last stages of deformation process during millions of years. For understanding of development of complex deformation in such crust regions it is necessary to study preconditions existed for the period of formation and becoming of structural ensembles. In addition to tectonophysics and paleostress reconstruction methods the mathematical modelling using continuum mechanics is irreplaceable [7]. Computer simulation on the basis of the finite element method [8, 9] for studying of the stress-strain state in thrusting rocks is used.

The first cover nappes of the Ukrainian Carpathians were formed at the end of Early Cretaceous times. In lateral cross-section from NE to SW for this time it is possible to locate the passive edge of the East-European platform, passed into flysch basement, and sedimentary basin limited on the other side by the block of the continental crust (Marmarosh massif). The geotectonic regime was defined by convergent interaction between flysch basement and continental block. This predetermined the thrust faults in a nearby part of basin sediments. In future the flysch complex was compressed and the front of thrust structures migrated in the pulsed-continuous style towards the platform.

The aim of this study is to investigate the dynamic factors (stresses and deformations) which control the compression of sedimentary layers during formation of thrust structures.



Модель 6L-0F **Модель 6L-2F** **Модель 6L-2F** **Модель 6L-3F**

Fig. 1. Computer models with different number of faults.

Geological data and short model description

The computer models on the basis of geological structural data are constructed. It has necessary simplifications and by three components is presented (Fig. 1). Two active elements are the platform edge passed into flysch basement by system of faults (on the right size of the model) and the block of a continental crust (on the left) as analogue of Marmarosh massif in the Inner Carpathians. Between them on the model a layered complex corresponded with Cretaceous sediments is constructed. The heterogeneous medium by six macrolayers with different mechanical properties and thicknesses according to stratigraphic levels in a cross-section of the Ukrainian Carpathians is presented. Generally, macrolayers model a sandwich-like structure with competent middle layer, weak viscous lower and brittle plastic upper layers. Their properties change stepwise across structure but each layer taken separately is homogeneous. The lower layer models thin-rhythmical flysch with equivalent thickness up to 700 m (detachment horizon), and a next one is already more competent due to increase of contained psammitic material. The third, most competent macrolayer (up to 600-700 m) is analogue of thick-rhythmical flysch and sandstones packs. Assumed Young's modulus for this layer is 35 GPa. Two next macrolayers gradually become less competent (25 and 15 GPa) and the least lithifical upper macrolayer characterized by brittle-plastic deformations are overlapped. The platform and massif are considered as more rigid bodies (Young's modulus equal to 100 GPa). The sedimentary basement we describe as contact conditions with rigid lower surface kinematically connected to platform. Other physical properties of the model for known literature data are averaged [3, 4].

For simulation of creep deformations in the sedimentary layers, specially for lower layer, the power law is determined [4]

$$\dot{\varepsilon}_{eqv}^{(creep)} = \gamma \cdot \left(\sigma_{eqv}\right)^{m},$$

where equivalent (von Mises) stresses σ_{eqv} depend on creep strain rate $\dot{\varepsilon}_{eqv}^{(creep)}$; γ, m – creep parameters, $-\log\gamma = 9 \div 12$ MPa^{-m} 10^{-6} s^{-1}, $m = 2-3$. For average stress σ_{eqv}=10–50 MPa it follows that equivalent linear viscosity $\eta_{eqv} = \gamma^{-1}\left(\sigma_{eqv}\right)^{1-m}$ equal to $\eta_{eqv} = 10^{19}$ - 10^{20} Pa·s. For σ_{eqv}=10 MPa and Young's modulus E_{eqv} = 20 GPa a period of relaxation $t_{relax} = \eta_{eqv} / E_{eqv}$ (that is time interval of decrease of stress level in $e \approx 2{,}71$ times), average hundreds of years and should be considered in the calculation.

Rheological properties of upper macrolayers are considered within model of elastic and brittle-plastic deformation with yield criterion taking isotropic hardening into account

$$\sigma_T^* = \sigma_T + E_T(\varepsilon_{eqv}^{(plast)},\ldots)\varepsilon_{eqv}^{(plast)}.$$

When we put $\sigma_T \approx 0.001$–$0.002\,E$ and residual strain accumulation increases to 5–10 % for competent material the instantaneous value of elasticity limit σ_T^* (equal to strength limit as provided by model of brittle fracture) is duplicated.

Between a layers system, the massif at the left, the basement and the platform on the right, and also between layers we set conditions of non-ideal mechanical contact with slipping between layers by Coulomb-Mohr law of friction [1]

$$\tau = \tau_0 + \mu|\sigma|,$$

where τ are friction forces, τ_0 – cohesion, μ –coefficient of friction; σ – contact pressure.

Proceeding from a unbiased fact about flysch basin contraction different cases of lateral movements of the left massif or the right platform (together with the basement) in direction of the layered complex are modelled.

The boundary condition for displacements is chosen equal to 1 cm/year that correlate to an average value fixed in modern lateral movements of the Earth's crust. The initial stages of compression traced up to 2–2.5 km.

Difficulties of a finite elements mesh reconstruction for greater plastic strains deformations are known [4, 9]. Also an algorithm of contact conditions between layers and faults sides versus hypotheses of continuum must be considered. This does not make it possible to follow on the base model all stages of deformation and thrust formation process with sufficient accuracy of structural heterogeneity description. Therefore we chose for computer simulation four genetically inherited models which show behaviour of layered sedimentary rocks during lateral compression.

The analysis of computer modelling results

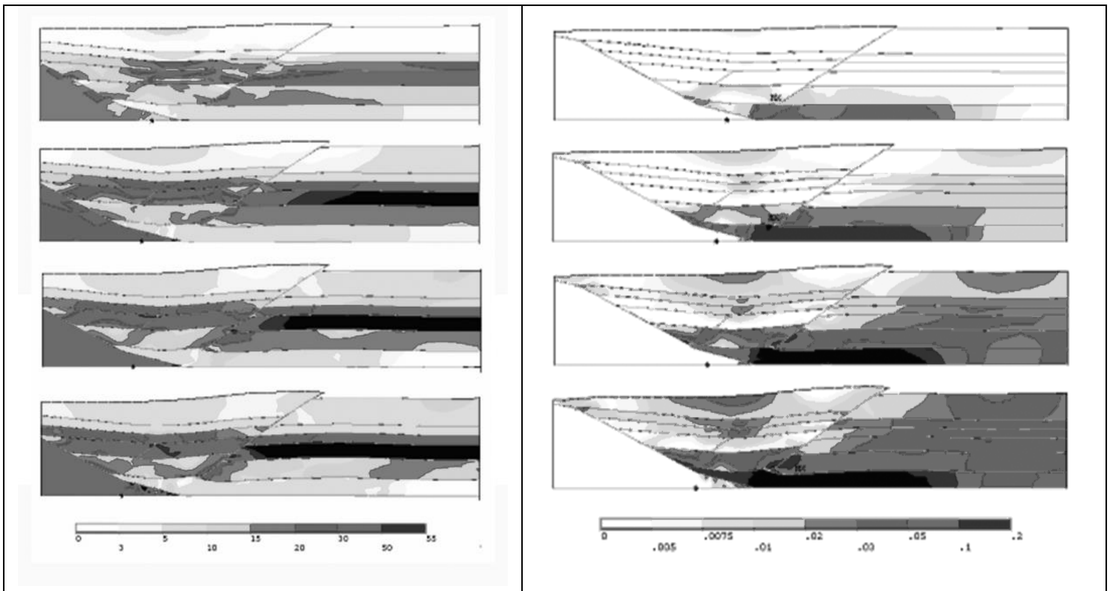
The investigation of stress-strain state is carried out on the several 2D-models, presented by cross-sections, for which hypotheses of plane deformation in the gravitational field are accepted. We are interested in finding a level of equivalent stresses (von Mises) σ_{eqv} and total finite strains ε_{eqv}. Actually they characterize stress and strain deviators, taking into account work-hardening of material, what is important for inelastic deformation. In aggregate they are primary factors of formation of different geological structures such as fault, fold or thrust. In particular, the value σ_{eqv} greater than a yield stress level testify or to plastic deformations, or to formation of faults in a fracture zone (a zone of release of elastic energy).

The first base model 6L-0F has the initial conditions presented above (Fig. 1). Geometry of a basin slope play here a key role in the interacting of lateral loadings and layers taken into account the sliding and friction between units of the model. From the platform side (with more steep ledges), competent layers control the shortening of the sedimentary basin, and from the massif, the compression is accompanied with slip of the lower layer upwards on a sub-horizontal part of a gentle slope that leads to bending of all sedimentary layers in this zone.

The greatest stresses arise nearby massif and have non-uniform distribution in macrolayers. Stress values in the third macrolayer and its lateral expansion zone are most significant. In other macrolayers high stress level arises a little later. In the compressed competent macrolayers the stresses localized in sinusoidal zones. The second model 6L-1F has a band of higher stresses exceeding strength limit, thus we assign a position of a hypothetical fault in a competent macrolayer where slipping contact conditions are defined. Compression of such model leads to expansion of the prime zone of critical stresses to the follow macrolayers. So, it is possible to assume development of the subordinated strike-slip faults into adjacent layers, especially into upper layers, forming a continuous plane through sedimentary rocks which can be a thrust fault. At the same time we show the similar zone of high stresses along competent macrolayers. There is a zone of a new hypothetical fault.

The next models 6L-2F and 6L-3F include more faults (Fig. 2, 3). Accordingly, the finite-element meshes are reconstructed. The assumption of faults position is grounded on the zones of higher stresses showed in the previous models. Process of construction of next models can be continued, however already after the third stage (the model 6L-3F) can be see a tendency (localization and inclination angle) to cyclic occurrence of such zones.

The complex stress-strain state is inherent for both models 6L-2F and 6L-3F. Lateral heterogeneity essentially in a subduction zone is expressed. The high stress level in nearby part of frontal fault and in the third competent macrolayer is observed too. It is necessary to note that their values are less than in previous models as a result of upward shifting along second fault plane and corresponding stress relaxation. Providing subsequent lateral compression, also stresses and thrust amplitude grows are increased. There are the lowered stress zones in fault bases, also relatively low values σ_{eqv} will be appear in apical parts of layered anticline within thrust body. Greater stress level is in third competent macrolayer. Partially they set off during slipping along the second fault and more less along third one, and again there are new sites of stress concentration in undamaged rocks. Also it is possible to localize the second order high stresses zones with other spatial orientation. They propagate into the upper macrolayers, and new thrust structures will be controlled by faults in competent macrolayer too.



a

b

Fig. 2. Fragment of cross-section in the subduction zone on the model 6L-2F: *a* – distributions of equivalent stresses σ_{eqv} (in MPa); *b* – total finite strains ε_{eqv} (dimensionless) for different stages during compression up to 2.0 km by step 0.5 km (top to bottom).

The layered anisotropy caused by essentially different mechanical properties and structural heterogeneity leads to redistribution of strains in comparison with compression of homogeneous block in gravitational field. For model 6L-2F accumulation of strains ε_{eqv} occurs in the lower layers due to creep. In detachment macrolayer there is a forcing a plastic material into thrusting zone, where development of folded structures also is possible. The higher level of total strains in the upper macrolayers of thrust body can testify to the latent damages of lower macrolayers. In the parts under thrust there is a significant strains accumulation which boundaries do not coincide with high stress zones.

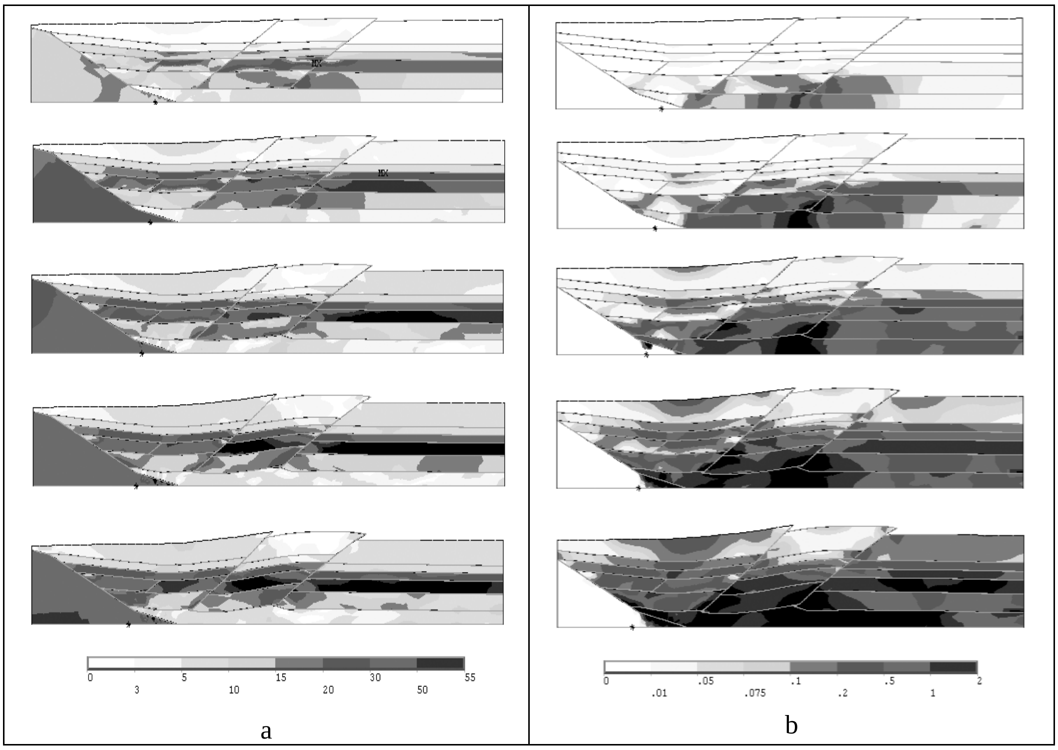


Fig. 3. Model 6L-3F: compression up to 2.5 km by step 0.5 km (top to bottom); notifications are similar to Fig. 2.

The layered anisotropy caused by essentially different mechanical properties and structural heterogeneity leads to redistribution of strains in comparison with compression of homogeneous block in gravitational field. For model 6L-2F accumulation of strains ε_{eqv} occurs in the lower layers due to creep. In detachment macrolayer there is a forcing a plastic material into thrusting zone, where development of folded structures also is possible. The higher level of total strains in the upper macrolayers of thrust body can testify to the latent damages of lower macrolayers. In the parts under thrust there is a significant strains accumulation which boundaries do not coincide with high stress zones.

Distribution of total strains in model 6L-3F is similar to previous one, but has its own peculiarities. Zones of greatest strain level in the lower viscous macrolayers associate with lower parts of faults, what is favourable for formation of nearby thrust folds. Also the anticline flexures in competent macrolayers are less deformed on front of thrusting.

Conclusions

1. It is important to apply heterogeneous finite-element methods in computer modelling of long-term geological process such as thrust wedge moving. The stress-strain state of real

sedimentary layers take into account elastic and plastic deformations and mechanically non-ideal contact both on detachment horizon and also between the macrolayers. Phenomena of a relaxation and relief of stresses owing to slipping must be considered too.

2. Zones of high compressive stresses in competent macrolayers control occurrence of faults, which can intersect sedimentary rocks, and assist of the formation of low-angle thrust structures. The criterion of Mises’ stresses for a choice of new faults location enables to provide initial stages and propagation of structures of thrusting kind.

3. High level of inelastic strains in the lower macrolayers especially in the detachment horizon and in the basis of thrust damages responses to nearby fault folded structures, which during movement of cover nappes are formed. Propagation of these strains into the upper parts of the cross-section by competent macrolayers is blocked.

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СКІНЧЕННО-ЕЛЕМЕНТНЕ МОДЕЛЮВАННЯ ОСАДОВОГО БАСЕЙНУ З НАСУВНИМИ СТРУКТУРАМИ

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За допомогою комп'ютерного моделювання на основі двовимірного методу скінченних елементів досліджуються динамічні умови тектонічного стиснення осадових шарів. Ці моделі представляють геотектонічну ситуацію для Українських Карпат у ранньокрейдовий час з урахуванням спрощеного перерізу. Геометрично цей поперечний переріз включає три частини: рухомий клин насуву, шаруватий осадовий комплекс і нерухомий похилий фундамент континентальної платформи. Побудовано низку генетично успадкованих моделей, в яких збільшується кількість розломних порушень насувного типу. Використано детальні чисельні моделі в рамках механіки суцільних середовищ: роздільна здатність скінченних елементів становить 500x100 м з біквадратичною апроксимацією переміщень. Ми вивчаємо напружено-деформований стан у неоднорідному середовищі зі суттєво неоднорідними механічними властивостями відповідно до флішового комплексу з перешаруванням компетентних та податливих шарів різної товщини. Лінійні розміри моделей: загальна товщина – до 5 км (включаючи 1 км гідростатичного тиску води) та 50–80 км у латеральному напрямку із врахуванням неідеального контакту із ковзанням між шарами та релаксацією напружень.

Результати комп'ютерного моделювання ілюструють деякі особливості деформування та розподіл напружень під час стиснення до 2,5 км. Побудовані карти – "миттєві знімки" – полів напружень та деформацій відповідно до переміщення клина насуву з кроком 0,5 км. Особливу увагу приділено зоні трійчастого контакту між переднім і заднім масивами гірських порід щодо крил розломів і підстильними шарами на горизонті відриву.

Поява періодичних по латералі зон із високим рівнем напружень контролює формування та розвиток незначно похилених розломів через осадові шари згідно з критерієм крихко-пластичного руйнування. Пластичні деформації, що моделюють повзучість для горизонту відриву, накопичуються в нижніх шарах поблизу розломів та утворюють у результаті складчасті структури, однак вони практично відсутні в апікальних частинах блоків насуву.

Самостійна перебудова моделей, які відстежують виникнення та еволюцію насувів або враховують неоднорідність у просторі, може бути завданням для майбутніх досліджень.

Ключові слова: скінченно-елементні моделі, структури насуву, напружено-деформований стан, шарувате середовище.

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