Thoughts on innovation and development of Geomechanics

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Abstract. Geomechanics is a discipline invented based on geological backgrounds of China, and has made great contributions to national key demands in both theoretical and practical aspects. However, both theoretical and practical challenges are facing this discipline. In this article, the authors analysed the developing history of Geomechanics, new demands raised by current social and theoretical development, its advantages, and pointed out business layout for developing Geomechanics in fulfilling national demands.

1. The developing history of Geomechanics

1.1. Gestation period

“The first phase (or aspect) of Geomechanics began with the study of the Carboniferous and Permian sediments in Northern China.” Li Siguang found that the Carboniferous andPermian strata in northern China were mainly composed of terrestrial strata. However, the concurrent strata in Southern China were dominated by marine strata. He then thought that the transgression and regression of seawater on the continents were global phenomena, and the movement of seawater was possible from the equator to the poles and from the poles to the equator. This may be due to the repeated “Fast-Slow” changes in the Earth’s rotation rate over the long period of geological history. He put forward the hypothesis of “Continental Brake” [1]. This hypothesis means that the formation of main structures of the Earth’s crust is related to the change of the Earth’s rotation speed. The core of this hypothesis is to answer the question of the crustal movement direction and the source of the driving force, which both the “Horizontal Movement” and “Vertical Movement” hypotheses had failed to resolve.

The second stage is to put forward the concept of “Structural System”. Li Siguang considered that various structural phenomena were “the remains of crustal movement at that time, and the real thing”. The study of crustal movements experienced by a region “requires an understanding of their individual nature, the forming processes, and the possible connections between them”, which is “fundamentally different” from that focusing solely on movements of large continents. In 1945, “The Basis and Method of Geomechanics” was published, summarizing the discipline of Geomechanics for the first time and of great significance for establishing the discipline of Geomechanics [2].

1.2. Innovative development period

Geomechanics theory plays an important guiding role in economic construction since 1949, in the following aspects:

(1) Advocating strategic eastward shift of petroleum general survey to achieve major breakthroughs.

According to the theory of Geomechanics, the focus of petroleum survey was transferred from Northwestern China to Northern China, Northeastern China and Northern Shaanxi. And in the following
years, oil-gas fields were discovered, including Daqing Oilfield, Dagang Oilfield, Shengli Oilfield, Jianghan Oilfield and other large-medium oil-gas fields [3-4].

(2) The research on Structure of Ore Field guided strategic mineral breakthroughs.

The theory that the Structure System controls ore distribution has guided the discovery of tungsten ore in southern Jiangxi, diamond ore in Shandong and Liaoning, gold ore in Liaoning, iron ore in Eastern Hubei and Southern Yunnan, especially the discovery of large uranium ore in Northern Guangdong [5-6].

(3) The “Safety Island” theory serves the “Big Three Line Constructions”.

The central government proposed “Big Three Line Constructions” for preparing for war and famine. The important arsenals and military facilities should be built in the western mountains where seismic and tectonic activities frequently happen. Li Siguang proposed the “Safety Island” theory, namely a relatively stable block as a site can be found in the tectonically active zone [7-8]. This theory solved important problems on the construction of large projects in areas of earthquake intensity within 8 degrees.

(4) Geomechanics theory summarization and discipline construction.

In 1962, the book “Introduction to Geomechanics” that integrated Li Siguang’s 40 years of practical experience was published. This book was a milestone in the history of Geomechanics research [9]. In 1970, Mr. Li Siguang compiled the first draft of “Astronomy, Geology and Paleontology”. The department or major of Geomechanics was formally established in Beijing Geological College, Wuhan Geological College, Changchun Geological College and Chengdu Geological College. Geomechanics courses were also offered in Geology departments of Sun yat-sen University, Zhejiang University and Northwestern University. The whole country geologists raised the upsurge of study and application of Geomechanics.

Geomechanics working methods have been widely used in petroleum, coal, all kinds of metallic and non-metallic minerals, hydrogeology, engineering geology, environmental geology, various geohazards (earthquake), geothermal and other fields. Many practical effects and economic benefits have been achieved. At the same time, it further enriched and deepened the theory of Geomechanics, and a series of theoretical achievements came into being [10-12].

1.3. Stable development period

Period: since the 1990s

Since the 1990s, the theory of plate tectonics prevailed, and the influence of Geomechanics was weakened, the courses of Geomechanics major in universities were cancelled, the academic thought of Geomechanics was greatly reduced. Geomechanics entered a period of stable development [10-12].

2. Major progresses and demand analysis in 21st century

2.1. New and positive progresses

(1) Important progresses have been made in structural system research and comprehensive mapping.

The first maps of “China’s Structural System Map” and “Distribution Map of Active Faults in China and Adjacent Areas (Scale 1:5,000,000)” covering both continents and seas have been compiled and repaired. Special maps of activity structures in important economic zones such as the Yangtze River Economic Belt, the Jiangdong New District, have been compiled.

(2) Remarkable achievements have been made in petroleum and mineral resources investigations and support for ore exploration breakthrough strategy.

The study of Tectonic Systems controlling oil distribution in the Middle and Eastern China has gained new understandings, and many tectonic types that control oil distribution have been established. The theoretical study of Ore-Field Structures has guided the breakthroughs in prospecting for iron polymetallic deposits in Altun Kaladawan area, gold deposits in Jiaodong, and ore-fields in the Qimantage of Qinghai province and Altai area.

(3) Remarkable results in the evolutionary mechanism of geological disasters and research on risk prevention and control.
Geomechanics study took an active part in the emergency investigation of geological disasters in Wenchuan and Yushu Earthquakes. The crustal stability and the assessment of the bearing capacity of the geological environment in disaster areas made important contributions to support Earthquake relief work. The instability evolution, risk assessment model and prevention and control technology of typical landslide hazards in Northwestern Loess Plateau have been proposed and demonstrated. The instability model of large-scale landslide disaster in karst mountain area of Southwestern China has been established.

(4) The assessment of active tectonic and regional crustal stability accurately serves the national needs and provides geological solutions for the planning and construction of major projects.

The investigations of active faults and regional crustal stability strongly supported the Beijing-Tianjin-Hebei coordinated development zone, Xiong’An New Area, Yangtze River Economic Belt, Hainan Free Trade Zone, Guangdong-Hong Kong-Macao Great Bay Area urban development planning and fault safety avoidance. These investigations also provided some suggestions on site optimization and geological solutions for major projects, such as Qinghai-Tibet Railway, Yunnan-Tibet Railway, Pan-Asia Railway, Lan-Yu Railway, West-East Gas Transmission, western route of water diversion from South to North, the Three Gorges water diversion and Capital International Airport.

(5) Series of achievements have been made on scientific and technological theoretical innovation and technological progress.

The late Precambrian studies of the North China Craton and the Phanerozoic continental deformations in Southern China have made important progress. The relationship between late Cenozoic surface processes and human civilization was explored. The polar basic geology research reached the international leading level. Internal and external dynamic coupling mechanism of geohazards and risk prevention and control theory and technology system was established. Basic research on engineering geology application in active tectonic area supported the planning and construction of major projects around the Qinghai-Tibet plateau. Tectonic and metallogenic mechanism of sandstone type uranium deposits and Wulagen lead-zinc deposits achieved innovative progress. New progress was made in the application of in-situ stress measurement techniques.

2.2. New demands in new era
(1) The transformation and upgrading of geological undertakings put forward new requirements for geological survey and research.

The service direction of geological survey should transfer from giving priority to mineral resource management support services in the past to providing support services to natural resources management, including mineral resources. Guiding theory should transfer from the traditional geological science to the Earth System Science. The development power should transfer from mainly relying on project to technological innovation and information construction.

(2) Key geological problems that restrict the investigation of clean energy and strategic minerals, such as shale gas, remain to be solved.

Clean energy, such as shale gas, is a strategic resource to support the adjustment of China's energy structure. At present, the overall level of exploration is low; the key problems need to be solved, such as the controlling effect of tectonic transformation on shale gas storage and enrichment and selection evaluation in complex tectonic areas.

(3) The new urbanization strategy requires more accurate and effective support services.

The geological work of new urbanization requires the assessment on the suitability of land space development and the geological safety of land space. Geological survey should transform from traditional conventional survey to demand-oriented unconventional survey, and from providing basic information to research and development of service products. In the new period of large-scale development and utilization of underground space in the future in China, the whole process management of planning, construction and operation of urban underground space and major projects puts forward new requirements on regional crustal stability evaluation.
4. National strategy and major project planning require scientific and precise engineering geological solutions.

The national strategy and the planning and construction of major projects require the geological work to transform from the traditional study of geological laws to serve the planning and control of land space and the safe utilization of underground space, and from macro qualitative understanding to quantitative fine detection, suitability evaluation of engineering construction and decision support. The expression of working process and results should shift from “geological” language to “engineering” language.

3. Theoretical advantages of Geomechanics

3.1. Originality of Geomechanics
Geomechanics is a set of special theories and methods created by Mr. Li Siguang based on the characteristics of tectonics in China and neighboring areas. Geomechanics, together with “Multi-Cycle” theory, “Fault Block” theory, “Geodepression” theory and “Wave Mosaic” theory constitute the five major tectonic theories in China.

3.2. Practicality of Geomechanics
As an original geological theory, Geomechanics guided the discovery of large oil and gas fields, such as Daqing oil field and Dagang oil field, Tungsten Ore Deposits in southern Jiangxi and large uranium deposits in northern Guangdong. These discoveries guaranteed national energy and mineral resources. In terms of disaster geology, Geomechanics has been widely used in earthquake prediction, slope stability, “Safety Island” determination, rock burst warning and tunnel deformation research and has obtained many economic benefits.

3.3. Geomechanics and General System Theory
The concept of General System Theory was first proposed by the Austrian American biologist, Bertalanffy, in a philosophical symposium at the University of Chicago in 1937 [13]. He pointed out that there are patterns, principles and laws applicable to the general system, regardless of the specific system type, the nature of its components and their relations. The system has important characteristics, such as integrity, organic relevance, dynamics, orderliness and predetermination. In 1968, the book “General System Theory (Foundation, Development and Application)” summarized the concept, method and application of General System Theory, and then the academic status of this discipline was established [13-15].

Geomechanics has distinct characteristics of being systematic since its foundation [16-17]. Mr. Li Siguang said many times that “Geomechanics is guided by the concept of Tectonic System”. Tectonic system is “the whole of tectonic belts composed of every structural elements of different shapes, properties, grades and orders, but with generative connections, and the rocks or blocks between those elements”. The Geomechanics believes that the phenomena of any geological structure do not exist in isolation. The whole of the geological structure phenomena accompanied by the formation of clusters and belts constitutes a unified structural system, which embodies Integrity, Correlation, Orderliness and Dynamics, and is basically consistent with the definition of General System Theory. The seven steps of core working method of Geomechanics is similar to the working procedure of modern “System Engineering”, which requires the research object to be modelled and simulated [16-17].

As for Integrity and Correlation, Geomechanics proposes that every Structural Trace must have an inseparable companion, and all Structural Traces occur in groups in the crustal parts composed of various rock strata and rock masses [16-17].

About Orderliness, Geomechanics points out that a complex structural system consisting of different orders and grades components, especially a large one, is often composed of many small sub-structural systems, which may be composed of several smaller structural systems [16-17].
As for Dynamic view, Geomechanics emphasizes that the tectonic stress field is still changing today, which can be obtained from in-situ stress measurements, and that the tectonic forces have not only linear movements but also rotational movements [16-17].

3.4. Geomechanics and Earth System Science

In 1983, NASA requested that Earth science is required to be reviewed as a system in which the parts interact, and subsequently published the monograph “Earth System Science” [18]. The monograph was written as a guide to the study of global change issues and lacked a comprehensive expounding of Earth System Science theories. At present, the definition of Earth System Science is to view the Earth as a unified system composed of interacting components such as the core, mantle, lithosphere, hydrosphere, atmosphere, biosphere and planetary system, focusing on the science of the interaction among the Earth’s components. The Earth System Science has five distinct views: the holistic and evolution view, the planet-global view, the interaction view, the complexity view and the interdisciplinary and unified view [18].

In the 1920s and 1930s, Geomechanics has regarded the Earth as a whole to study the relationship between lithosphere and hydrosphere, atmosphere, biosphere and the lower crust. The “Continental Brake” hypothesis was proposed then. The book “Astronomy, Geology, Paleontology” (1970) can be said as a masterpiece that embodied Earth System Science in China and even internationally.

At present, the Earth System Science presents two directions, the first is that related disciplines of the Earth science are more to promote the Earth system discipline from the concept, making the original subject more coruscate new vitality. Hence some boundaries among disciplines are blurred, and the cross penetration among disciplines is strengthened, which promotes the formation of new branches. The second is to promote and develop Earth System Science as a new subject to reveal the essence and regularity of the Earth system.

At present, Earth System Science is more likely to reflect the first trend, that is, the related branches of Earth science adopt the General System Theory and studying one or several sub-systems under the background of global system. In the strict sense, the science of revealing the Earth system still needs further efforts. If Earth System Science represents the development direction and trend of Earth science, Geomechanics can be regarded as the current realistic stage. Geomechanics not only includes General System thoughts in theory, but also has extensive practicability and is practical in application, which has been proved in the application in exploration and development of petroleum, coal, all kinds of metal ore, as well as the application in disaster geological investigation and prevention [17].

4. Business layout of Geomechanics in the new era

The specialty characteristics of Geomechanics should be highlighted and the leading position of “geotectonic and internal dynamic action” in various disciplines should be strengthened [19]. Adhering to the core of Innovative Development of Geomechanics, every effort will be made to build four business fields, namely, Land Space Geological Security Assessment, Regional Geology and Deep Structure Research, Oil and Gas Geomechanics and Ore-Field Structure Research, and Polar Geology Research. Relying on the existing bases and laboratories, two state-level scientific and technological innovation platforms, a key laboratory of active tectonic and crustal stability and a national geostress monitoring network are planned to be built.

4.1. Innovative Development of Geomechanics

Systematic advantages and characteristics of Geomechanics should be given full play to precisely fulfil China’s major strategic needs. Under the background of modern Earth science research, modern information technology and various detection technologies should be fully utilized, through the investigation of the interactions of basic geology with multi-layers of the Earth, to study the effect of deep Earth process on the evolution of the shallow surface environment and its resource and environmental utility, and to compile new tectonic system maps in different levels, and finally to achieve
innovative development of Geomechanics theory with the core research content on continental deformation and continental dynamics as advocated by Li Siguang.

4.2. Land Space Geological Security Assessment
(1) Evaluation of active structure and regional crustal stability
   Based on Geomechanics theory and method of geological and geophysical techniques, combined with the high precise chronology and deep Earth exploration technology, researches on structure of exquisite space-time evolution and deep Earth mechanism will redisplay the active tectonic evolution process of time and space and development trend will be forecasted. The active tectonic detection and the quantitative research of the evolution of time and space in important economic zone and the major engineer area will be finished, and multi-objective survey research findings faced to important economic zone and the major project area will be formed. Theories and technologies for the quantitative evaluation on crustal stability will be innovatively developed. Mandatory national standards will be established. An evaluation system platform of crustal stability based on the scientific data of active structures at the national level will be built to support and serve national strategies, major projects or important urban planning and construction.

   (2) Risk assessment, prevention and control of geological disasters
   Major geological disasters forming pattern and dynamics mechanism theory should be deepened. Deformation characteristics of geological disasters induced by earthquake, rainfall, and engineering activities should be revealed. Instability of geological disaster body and dynamic evolution process should be simulated. Early identification method based on remote sensing technology such as InSAR should be explored. Development regularities and geological disaster risk forecast and early warning of regional geohazard should be researched. A multi-factor, multi-working condition, multi-scale and multi-layer technical system for risk assessment on geological disasters should be built in an integrated way to provide scientific basis for spatial planning and disaster risk control from the source.

   (3) Regional engineering geological survey
   Centring on the active faults and key engineering geological problems faced by the planning and construction of national major projects, the research on the engineering characteristics of special rock and soil mass, the mechanism of geological disasters of major projects under the coupling action of internal and external dynamic, the stability of high slope and the stability of surrounding rock of deep buried tunnels should be carried out. To provide geological security guarantee for the construction of shallow surface engineering and the requirement of safe development of underground space, the internal and external dynamic coupling of engineering geological survey and evaluation and its solution research should be strengthened, and the quantitative evaluation on the suitability of engineering construction should be deepened.

   (4) In-situ stress measurement and monitoring
   Basic theories and technical methods for geostress measurement and monitoring should be developed, to strive to reach the international leading level in aspects of geostress measurement theories, technical methods and active tectonic stress field research. A real-time geostress monitoring network system and a platform for the release and social sharing of geostress information in major active tectonic zones should be researched and developed to provide reliable data and technical support for basic geodynamics research, internal dynamic geological disaster prevention and control, location and construction of major national projects, and the development and utilization of deep resources.

4.3. Regional Geology and Deep Structure Research
(1) Basic geological survey of the interaction between surface processes and geosphere
   The surface survey and a variety of modern detection, information technology should be comprehensively utilized to carry out regional geological survey with the integrated “Satellite-Unmanned Aerial Vehicle-Ground” monitoring method systematically, and to find out the process of weathering-erosion -accumulation process of material in surface crust in key areas such as the northeastern margin of Qinghai-Tibet Plateau, northern desert, and southwestern karst, and to establish
the late Cenozoic continental tectonic framework, depositional filling process, the response to environmental changes and geodynamic background. The basic geological survey of the interaction between surface processes and geosphere should be carried out to reveal the interaction between different layers of the Earth’s surface system and the exchange law of material and energy, so as to provide basic geological data for the management of natural resources and the construction of ecological civilization.

(2) Continental deformation and ancient continental reconstruction

Studies on Precambrian tectonic evolution and supercontinent dispersion of North China Craton, Mesozoic tectonic deformation and continental tectonic evolution of the Southern China and Northern China, formation and evolution process of the Qinghai-Tibet Plateau, should be promoted. Research on global and regional paleo-plate movement and geotectonic evolution, internal deformation of continental and deep geological processes should be carried out to lead the research field of continental deformation and paleo-plate reconstruction, and to provide support for solving major fundamental geological problems and deep geological exploration.

4.4. Oil and Gas Geomechanics and Ore-Field Structure

(1) Geological survey on petroleum and shale gas

Tectonic System’s control on the formation and distribution of petroleum and shale gas should be taken as the main line [20], combining with the geophysical and geochemical exploration, drilling and other means to make a comprehensive research, to find out the formation and evolution of basins that bearing petroleum or shale gas, to analysis the dynamics mechanism of basin forming-hydrocarbon forming-accumulation that controlled by tectonic evolution, to construct evaluation method system of tectonic evolution and petroleum accumulation and preservation, to develop petroleum geological mechanics theory, and to achieve a major breakthrough of oil and gas discovery in the geology survey [21].

(2) Ore field structure investigation and ore prospecting prediction

Based on the structural analysis of ore-field, by using the principles and methods of tectonic geology and ore-deposit science, studies on the formation and distribution of ore-field, and transformation of ore-field, ore-deposit and ore-body that controlled by structure should be carried out. Through the three-dimensional modelling and numerical simulation of ore-forming tectonic system, the model of tectonic ore-controlling and ore-prospecting will be constructed to guide the ore-prospecting prediction.

4.5. Polar Geology Research

The major geological events in the North and South Polar continents should be clarified, the process of plate convergence-accretion-breakup-separation in the South and North Polar regions, and resources and environmental effects should be investigated, so as to further improve the level of Polar geoscience research in China, and to stay at the forefront of Polar geoscience research internationally.

4.6. Plan advantageous platforms

(1) Building a key laboratory for active tectonic and crustal stability evaluation

Theory of quantitative evaluation technology system of the Earth’s crust stability in active tectonic zones should be developed. Focusing on internal and external forces coupling mechanism, the key technology on hidden dangers identification of geohazard and risk prediction and prevention can be innovated, the basic theory research of engineering geological applications in active tectonic area will be deepened and expanded, the bottleneck of critical theory and technology will be broken.

(2) Building a national geostress monitoring network

Applying the latest technologies, such as high-precision continuous observation of drilling strain, a national geostress monitoring network should be established in areas around major tectonic zones, important economic zones and city clusters, major project construction areas and energy and mineral exploration development zones in mainland China. The research and development of the geostress real-time monitoring network system and the geostress information release platform of the main active
tectonic belt can provide data support for the theoretical innovation of Geomechanics, geological disaster monitoring and early warning, national major project construction planning, and deep resource development.

5. Summary
Geomechanics has made outstanding contributions in both theoretical and practical fields fulfilling national key demands. But it is also facing challenges in both theoretical and practical fields under the new situation. Rebuilding confidence, refining and enhancing already existing progresses and deploying future research concentrated on providing Geomechanics solutions to key national needs are the main strategies for conquering these challenges.

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