Study on plastic-brittleness mechanical properties and failure law of deep brittle shale under complex mechanical environment of wellbore

Sun Hang-rui¹, Liu Hou-bin¹, Cui Shuai¹, Wang Jia-jun¹, Han Xu²

¹State Key Laboratory of Oil and Gas Reservoir Geology and Exploitation, Southwest Petroleum University, Chengdu, 610500, China
²South Sichuan Gasfield, Southwest Oil & Gasfield Company, Luzhou, 646000, China

E-mail: qfylhb@swpu.edu.cn, ORCID:0000-0003-4849-972

Abstract. China has abundant deep shale gas resources, but the complex problem of wellbore collapse in horizontal well drilling is prominent. Aiming at the problem of wellbore collapse in deep brittle shale, deep shale’s mechanical loading simulation experiment scheme under a complex wellbore alternating mechanical environment was carried out. Triaxial mechanical tests of shale under different confining pressures are carried out in this paper. The stress-strain and acoustic characteristics of shale under different confining pressures during loading are analyzed, and rock’s stress-strain and dynamic acoustic response mechanisms are discussed. The mechanical constitutive relationship, plastic brittle mechanical properties, and anisotropic characteristics of deep brittle shale under a complex mechanical environment of the wellbore are studied. The collapse failure law of deep brittle shale wellbore is also analyzed. The results show that the deep brittle shale has high mechanical strength, is highly brittle, and developed bedding fractures. Under the condition of low confining pressure, the stress-strain curve of shale before fracture is mainly elastic deformation, and the plastic mechanical damage is not obvious. With the increase of confining pressure, shale’s compressive strength and elastic modulus increase, and its plastic damage gradually become apparent. In the process of triaxial loading, the change of acoustic wave velocity increases first and then decreases. With the increase of confining pressure, the peak stress point becomes smaller and smaller, revealing the plastic failure characteristics of rock under high confining pressure. The brittle features of shale under low confining pressure are obvious. The fracture morphology of rock after stress is mainly the splitting tensile fracture, and the number and size of cracks are significant. Under high confining pressure, shale exhibits plastic failure, and plastic damage characteristics are evident in the process of rock sample failure. Rock sample failure is mainly manifested as single shear failure or conjugate shear failure with tensile fracture. The experimental results show that the failure mode of brittle shale under a complex wellbore mechanical environment is mainly tensile splitting and shear coupling failure. The research experimental results of this paper have particular guiding significance for the study of wellbore stability during drilling in the deep brittle shale formation.

1. Introduction
The downhole environment of deep shale reservoirs is very complex, resulting in frequent downhole accidents. It is imperative to know the damage information of rock from deformation to failure to guarantee wellbore stability. Acoustic waves have certain physical properties as it propagates through rock formations. When it passes through the rock sample, the information of changes in the rock’s internal structure and mechanical properties will be recorded by the acoustic wave. Thus, the damage law of rock can be observed by the change of acoustic characteristics. The change of acoustic wave velocity can effectively characterize the damage degree of the rock mass. Rocks under load will produce cracks leading to the change of acoustic wave velocity, which is the crack effect of acoustic waves [1]. In 1992, Luo J H et al. [2] studied the relationship between the failure process of rock under uniaxial and true triaxial loading and the acoustic parameters of rock mechanics and proposed that the acoustic parameters could determine the different stages of the failure process under loading. In 1999,
Zhao M J et al. [3] studied the relationship between acoustic characteristics and changes in rock mechanical properties during uniaxial compression. In 2009, Liu X J et al[4] tested the variation law of acoustic wave velocity and spectrum characteristics of sandstone with low porosity and low permeability under different confining pressures. In 2012, Liang T C et al. [5] compared and analyzed the change rule of acoustic emission and wave velocity in the process of rock damage to judge the damage state of rock.

In 2015, Yan P et al. [6] established the relationship between the rate of change of acoustic velocity and the range of change of mechanical parameters of rock mass by conducting triaxial loading experimental study on rock samples with pre-loss. In 2016, Li H R et al. [7] studied salt rock’s damage and deformation characteristics under triaxial and multistage cyclic loading and the variation law of ultrasonic wave velocity and acoustic emission. In 2019, Sun Q P et al. [8] carried out a dynamic triaxial compression test under different strain rates to study the influence of bedding direction on the failure mode, strength, and energy dissipation characteristics of shale under dynamic load. In 2020, Li J H et al.[9] proposed five stages of wave velocity variation during rock loading, which provided a reference for predicting geological disasters.

In the process of oil drilling and production, the stress of the surrounding rock will be redistributed, which will affect the mechanical strength characteristics and damage law of the rock. Therefore, it is necessary to understand the law that the rock’s mechanical properties and damage characteristics change with the change of the external force. Through investigation and analysis, most scholars focus on studying the mode of shale after loading and failure under different conditions but seldom analyze the damage law during the loading process of rock. Therefore, to study the damage law of shale in a complex environment, the monitoring experiment of acoustic wave characteristic changes in the triaxial compression process of shale under high and low confining pressures is carried out. The relationship between acoustic wave and rock mechanical properties is used to determine the state of rock damage to provide a basis for borehole stability and the prevention of underground accidents.

2. Material

2.1. Rock sample
The rock samples used in this experiment are taken from 3500 m deep well section of Longmaxi Formation in Changning Block. According to the production requirements of the standard sample, it is cut into a cylinder of 25 × 50 mm in size. Density, wave velocity, porosity, and permeability tests were carried out to select rock samples with similar properties. Test results for selected rock samples are shown in Table 1.

|     | Density (g/cm³) | Porosity (%) | Penetration (mD) | Vp (ms⁻¹) | Vs (ms⁻¹) |
|-----|----------------|--------------|------------------|----------|----------|
| A-0 | 2.5301         | 3.92         | 0.0840           | 4659.5   | 2617.9   |
| A-1 | 2.5284         | 3.73         | 0.0690           | 4707.9   | 2731.5   |
| A-2 | 2.4972         | 3.86         | 0.0779           | 4665.7   | 2668.8   |
| A-3 | 2.5255         | 3.96         | 0.0698           | 4656.8   | 2736.1   |
| A-4 | 2.5114         | 4.15         | 0.0972           | 4683.5   | 2697.9   |
| A-5 | 2.5319         | 4.33         | 0.0843           | 4644.3   | 2680.9   |
| A-6 | 2.5301         | 3.73         | 0.0763           | 4720.0   | 2719.4   |
| A-7 | 2.4846         | 3.84         | 0.0756           | 4680.2   | 2733.5   |
| A-8 | 2.5142         | 3.91         | 0.0844           | 4753.4   | 2795.6   |
| A-9 | 2.5089         | 4.41         | 0.0893           | 4668.5   | 2675.5   |
| A-10| 2.5259         | 4.16         | 0.0824           | 4690.7   | 2714.2   |
| A-11| 2.5276         | 4.03         | 0.0752           | 4651.9   | 2678.4   |
| A-12| 2.5263         | 4.25         | 0.0876           | 4616.8   | 2636.7   |
2.2. Mineral composition analysis and microstructure characterization of rock samples

The mineral composition of rocks affects their mechanical properties, deformation characteristics, and homogeneity. The brittle minerals determine the brittle plasticity of the rocks. Therefore, the test and analysis of the mineral composition of rocks are of great significance to the study of wellbore stability. The mineral composition of shale was analyzed by XRD diffraction equipment of State Key Laboratory of Petroleum Geology and Development Engineering of Southwest Petroleum University. The test results are shown in Fig. 1. The mineral composition of the deep shale of Longmaxi Formation is complex, mainly quartz minerals. The content of quartz is high, approximately 34%, and contains a small amount of dolomite and calcite. The average clay mineral content of Longmaxi Formation is 26%, which mainly comprises a large amount of chlorite and illite.

In contrast, the content of montmorillonite with high expansion capacity is very low. This implies that the shale was hard and brittle with weak hydration and expansion capacity. In general, the deep shale of Longmaxi has high hardness, brittleness, and weak hydration expansion ability.

The study on the microstructure characteristics of rocks can reveal the mechanical properties of rocks and wellbore stability from a microscopic point of view. The environmental scanning electron microscope of Southwest Petroleum University was used to test the microstructure characteristics of shale samples from the Longmaxi Formation in Changning Block. The scanning results are shown in Fig. 2. It can be seen from the SEM images that the bedding fractures of the shale in the Longmaxi Formation are developed, and the layered structure is evident. In addition, it can be seen that there are cracks and bedding intersect, leading to rock block fracture. This kind of rock sample easily experiences slip failure at the bedding joint, and the cross seam with the bedding further weakens the mechanical weak plane effect of the bedding joint.

![Figure 1. Mineral composition content of Longmaxi Formation shale.](image1)

![Figure 2. SEM photo of Longmaxi Formation shale.](image2)

3. Experimental method

The experimental equipment used in this experiment is a self-made confining pressure triaxial rock mechanics test machine made by the underbalanced drilling laboratory of Southwest Petroleum University. The equipment can be used for uniaxial and triaxial compression tests of rock samples and test of longitudinal and shear wave velocity of rock samples during loading. The can generate and maintain a maximum confining pressure of up to 100 MPa, and the maximum axial load of 1000 kN. The laboratory equipment is shown in Fig. 3.
In this paper, the following experimental scheme is designed for the complex stress environment of shale, and the indoor triaxial mechanics experiment is designed. The rock mechanical properties and damage characteristics of shale under low confining pressure to high confining pressure were studied. The confining pressure range was 0–60 MPa, the interval was 5 MPa, and the loading rate was 0.5 MPa/s. The loading method increases the set value of confining pressure after the pressure head is in close contact with the rock, keeps the confining pressure unchanged, and continues to increase the axial stress until the rock is damaged. The acoustic information of rock damage during the whole loading and unloading process is collected in real-time until the end of the test.

4. Experiment result and discussion

4.1. Triaxial experimental results and analysis

The triaxial compression tests of shale under different confining pressures are loaded, and the experimental data are shown in Table 2. With the increase of confining pressure, rock’s compressive strength and elastic modulus gradually increase, and the Poisson’s ratio shows a decreasing trend. The full stress-strain curves of rock samples are drawn from the experimental data, as shown in Fig. 4. It can be seen from the figure that the relationship between stress and strain of shale under low confining pressure is approximately a straight line, indicating that shale is dominated by elastic deformation under low confining pressure. When the confining pressure is higher than 30 MPa, under the condition of low stress, the stress-strain curve is approximately a straight line. When the stress increases by a particular value, the curve appears to bend downwards, and the slope of the curve becomes smaller and smaller with the increase of stress until failure. The increase of confining pressure makes the plastic stage of shale more and more prominent. The trend of various characteristics of rock sample curve indicates that shale transforms from elastic body to elastic-plastic body, which is also an objective manifestation of relatively weak brittleness and gradually enhanced ductility of shale.

The characteristic points on the stress-strain curve of the compression experiment can explain the damage law of rock in the failure process. The variation of ultimate compressive strength, yield strength, and expansion point strength under different confining pressures is shown in Fig. 5. Different confining pressures are set to simulate the downhole stress environment of rock at different depths. With the increase of confining pressure, the ultimate compressive strength of shale gradually increases. For example, when the confining pressure is 60 MPa, the ultimate compressive strength of rock increases significantly, indicating that the mineral composition and structure of rock itself affect the regularity of ultimate compressive strength with the increase of confining pressure.

The yield point is the turning point of rock from elastic deformation to plastic deformation, and the yield strength is the stress value at the endpoint of the straight line segment on the stress-strain curve. The increase of yield strength of rock samples with the increase of confining pressure is characterized by the continuous increase of elastic energy stored in the internal before the failure of rock samples, which is also reflected in the enhanced ability of rock samples to resist deformation and failure. The
strength of the expansion point represents the starting point of unstable fracture of a rock sample, and the strength value of the expansion point also increases significantly with the increase of confining pressure, which indicates that the expansion of shale micro-cracks is inhibited by confining pressure. Thus the development of shale micro-cracks under high confining pressure becomes more challenging.

The stress difference between compressive strength and expansion point strength can characterize the plastic characteristics of rock samples. It can be seen from the diagram that the stress difference between the two increases with the increase of confining pressure, indicating that the plastic characteristics of rock samples are more and more evident with the increase of confining pressure.

Table 2. Triaxial mechanical experimental results.

| Confining pressure (MPa) | Compressive strength (MPa) | Elasticity modulus (Gpa) | Poisson’s ratio |
|-------------------------|----------------------------|-------------------------|----------------|
| A-0                     | 0                          | 105.666                 | 14.22          | 0.217          |
| A-1                     | 5                          | 153.74                  | 14.50          | 0.208          |
| A-2                     | 10                         | 185.817                 | 14.78          | 0.201          |
| A-3                     | 15                         | 219.386                 | 15.05          | 0.193          |
| A-4                     | 20                         | 229.943                 | 15.38          | 0.188          |
| A-5                     | 25                         | 275.122                 | 15.56          | 0.174          |
| A-6                     | 30                         | 291.906                 | 16.12          | 0.169          |
| A-7                     | 35                         | 299.181                 | 16.30          | 0.163          |
| A-8                     | 40                         | 313.898                 | 16.68          | 0.158          |
| A-9                     | 45                         | 330.759                 | 17.34          | 0.151          |
| A-10                    | 50                         | 343.08                  | 18.36          | 0.146          |
| A-11                    | 55                         | 359.592                 | 19.45          | 0.141          |
| A-12                    | 60                         | 416.129                 | 21.70          | 0.135          |

4.2. Characteristics of vertical and horizontal wave velocity during loading

In the triaxial loading process of rock, the increase of axial stress, the damage process, and the internal damage structure of shale can be shown by acoustic characteristics. The changes of P-wave and S-wave velocities of rocks under different confining pressures are shown in Fig. 6. With the increase of axial pressure, rock samples’ P–S wave velocity increases at first and then decreases, mainly due to the micro-cracks and bedding in shale. In the early stage of the triaxial compression test, the micro-cracks and bedding closure of shale lead to the compaction of rock samples and the rapid increase of acoustic velocity. When the axial stress increases to a certain extent, the velocity of P–S wave begins to decrease slightly, indicating that the shale begins to produce micro-cracks. The propagation and extension of micro-cracks make the velocity of acoustic waves start to drop significantly. The axial...
stress exceeds the compressive strength of the rock, and the rock sample is unstable. The crack volume of the specimen reaches the peak, and the longitudinal and shear wave velocity decreases sharply.

![Figure 6](image)

**Figure 6.** The relationship between longitudinal and lateral wave velocities, axial strains and axial stresses under different confining pressures.

The acoustic variation characteristics of rock samples are shown in Table 3. The peak point stress ratio of the rock sample is the ratio of axial stress to compressive strength at the peak wave velocity of rock, which is an eigenvalue reflecting the plastic deformation of rock during damage. The smaller the peak stress ratio is, the greater the proportion of plastic stage in rock loading. With the increase of confining pressure, the smaller the peak stress ratio is, the stronger the plastic characteristics of rock are. The velocity change rate is the ratio of the difference between the peak wave velocity of the rock sample and the wave velocity at the peak stress to the peak wave velocity. Based on the damage definition method of acoustic wave velocity, the longitudinal wave change rate represents the damage variable of rock samples at peak stress [11].
4.3. The response mechanism of stress-strain and acoustic characteristics

The damage process of shale is a process of micro-cracks first compaction and then expansion. The total stress-strain curve under triaxial test can be divided into four stages from the damage angle and acoustic wave change: compaction stage, elastic deformation stage, plastic deformation stage and failure stage, as shown in Fig. 7.

Compaction stage: At the initial loading stage of the triaxial test, with the increase of axial stress, the internal cracks of rock gradually closed under the action of load, and the acoustic velocity of rock samples increased rapidly. The stress-wave velocity curve of the rock sample is convex with the increase of the compaction degree of the rock sample, indicating that the acoustic wave characteristics are the rate of the increase of the wave velocity of the rock sample. The variation of wave velocity of rock samples in this valence section is mainly affected by the porosity of rock samples.

Elastic stage: In this stage, the mineral particles of the rock become denser, and there is no initial crack propagation and new crack generation in the rock. The acoustic characteristic curve shows that the wave velocity increases with the increase of stress, and the acoustic velocity reaches the peak at the end of the elastic stage. The stress increases linearly with the strain in the total stress-strain curve, and the rock deformation shows stable elastic deformation.

Plastic deformation stage: When the acoustic velocity changes from increasing to decreasing, the rock deformation enters the plastic stage. The initial cracks in the rock sample began to expand and generate new cracks under stress, and the acoustic velocity also decreased rapidly. The slope of the stress-strain curve began to deviate from the straight line, and the change of wave velocity was mainly affected by the formation of micro-cracks in the rock sample.

Damage stage: When the axial stress reaches the ultimate compressive strength of the rock sample, the cracks in the rock form a macroscopic fracture surface. The stress-strain curve decreases abruptly, the crack volume of rock increases, and the acoustic velocity decreases sharply. At this stage, the change of wave velocity of the rock sample is mainly affected by the macroscopic cracks of the rock.

Table 3. Analysis of rock acoustic velocity data.

| Confining pressure (MPa) | Peak point stress ratio | P-Speed variation rate |
|-------------------------|------------------------|------------------------|
| A-0                     | 0                      | 0.853                  | 0.11                   |
| A-1                     | 5                      | 0.739                  | 0.09                   |
| A-2                     | 10                     | 0.727                  | 0.12                   |
| A-3                     | 15                     | 0.721                  | 0.08                   |
| A-4                     | 20                     | 0.712                  | 0.09                   |
| A-5                     | 25                     | 0.705                  | 0.08                   |
| A-6                     | 30                     | 0.697                  | 0.10                   |
| A-7                     | 35                     | 0.689                  | 0.09                   |
| A-8                     | 40                     | 0.681                  | 0.09                   |
| A-9                     | 45                     | 0.674                  | 0.15                   |
| A-10                    | 50                     | 0.661                  | 0.10                   |
| A-11                    | 55                     | 0.652                  | 0.13                   |
| A-12                    | 60                     | 0.642                  | 0.12                   |
4.4. Analysis of failure pattern of shale

The damage pattern and fracture mode of shale vary significantly under different conditions. Fracture morphology of shale under uniaxial conditions is shown in Table 4. When rock samples are compressed under uniaxial conditions, when the axial stress reaches the peak strength and the sudden release of storage deformation energy, multiple longitudinal macroscopic cracks quickly penetrate through the rock samples, making the rock samples lose their continued bearing capacity. As a result, rocks form multiple irregular fine longitudinal cracks and small failure surfaces, accompanied by fine debris falling. Its fracture morphology has prominent tensile failure characteristics of layered hard, brittle rocks, with apparent anisotropy.

Table 4. Failure patterns of shale samples under uniaxial conditions.

| Confining pressure | Photo of rock sample before destruction | Photo of rock sample after destruction | Fracture description map |
|--------------------|------------------------------------------|----------------------------------------|--------------------------|
| 0Mpa               | ![Image](image1.png)                     | ![Image](image2.png)                   | ![Image](image3.png)     |

It can be seen from Table 5 that the failure shapes of shale are different under different confining pressures. The brittle splitting failure of shale mainly occurs at 0–20 MPa. There is a vertical crack on the surface of the rock sample, and there is also a transverse crack in the middle and above, accompanied by a small amount of debris falling. There is a meshing phenomenon on the surface of some cracks, and there is a concave–convex undulating crack surface. With the increase of confining pressure, the failure mode of the rock sample begins to transition to plastic failure. When the confining pressure was greater than 25 MPa, the rock samples began to shear failure, and the rock samples gradually transformed into single fracture surface and local failure mode. The number of cracks after failure was significantly reduced, and the fracture surface was clear. When the confining pressure is 60 MPa, there is no obvious fracture surface on the rock sample, which is replaced by a high-stress belt. Rock failure angle is the angle between the failure surface and the direction of the minimum principal stress. When the confining pressure increases from 0 MPa to 60 MPa, the rock failure angle decreases gradually, and the confining pressure is inversely proportional to the rock failure angle. Generally, the triaxial compression of shale is greatly affected by confining pressure. The fracture mode of rock
samples under confining pressure is mainly shear fracture, and the fracture mode is anisotropic, as the failure modes are also different.

Table 5. Fracture modes of shale under different confining pressures.

| confining pressure | Rock sample destruction photo | Fracture description map | confining pressure | Rock sample destruction photo | Fracture description map | confining pressure | Rock sample destruction photo | Fracture description map |
|--------------------|-------------------------------|--------------------------|--------------------|-------------------------------|--------------------------|--------------------|-------------------------------|--------------------------|
| 5 MPa              | ![Image](image1.png)          | ![Image](image2.png)     | 25 MPa             | ![Image](image3.png)          | ![Image](image4.png)     | 45 MPa             | ![Image](image5.png)          | ![Image](image6.png)     |
| 10 MPa             | ![Image](image7.png)          | ![Image](image8.png)     | 30 MPa             | ![Image](image9.png)          | ![Image](image10.png)    | 50 MPa             | ![Image](image11.png)         | ![Image](image12.png)    |
| 15 MPa             | ![Image](image13.png)         | ![Image](image14.png)    | 35 MPa             | ![Image](image15.png)         | ![Image](image16.png)    | 55 MPa             | ![Image](image17.png)         | ![Image](image18.png)    |
| 20 MPa             | ![Image](image19.png)         | ![Image](image20.png)    | 40 MPa             | ![Image](image21.png)         | ![Image](image22.png)    | 60 MPa             | ![Image](image23.png)         | ![Image](image24.png)    |

5. Conclusion

In this paper, the rock mineral composition, content distribution, and microstructure characteristics of shale in Longmaxi Formation shale are tested. Through triaxial mechanical experiments under different confining pressures, the mechanical properties of shale under different confining pressures and the variation characteristics of acoustic waves during loading were studied. The main conclusions are as follows:

(1) The deep shale of Longmaxi Formation is hard brittle shale with weak hydration expansion capacity. However, the rock mass is relatively dense, with developed bedding, apparent layered structure, and high mechanical strength.

(2) The trend of various characteristics of rock sample curve indicates that the increase of confining pressure makes shale transform from elastic body to elastic-plastic body, which is also an objective manifestation of relatively weak brittleness and gradually enhanced ductility of shale. Furthermore, the strength of each characteristic point of shale increases with the increase of confining pressure, and it shows a pronounced confining pressure effect under high confining pressure.

(3) In the triaxial loading process, the overall trend of the change of acoustic velocity is first increased and then decreased. As a result, the peak stress point continually gets smaller with the
increase of confining pressure, indicating that the proportion of plastic deformation of rock also continually increases. As a result, the plastic characteristics of rock samples become continually pronounced.

(4) Through the real-time monitoring of wave velocity information of rock mass during triaxial loading, the variation characteristics of the acoustic wave in different damage stages of rock are mastered, which provides early warning for subsequent rock instability and borehole stability.

(5) The failure of shale under low confining pressure is mainly split tensile fracture. When the confining pressure increases to 25 MPa, the shale changes from brittle to plastic shear failure. When fracture angle and fracture number decrease with the increase of confining pressure, the rock sample is damaged. The confining pressure in-effect hinders the slip of crystal and the formation of cracks and inhibits the initiation and deformation of rock pores.

References
[1] Ding J Y 1982 Influence of crack in rock on acoustic wave propagation Nonferrous Metals. (02):7-12
[2] Luo J H, Cai Z L, Liu K, Li X 1992 Determination of different stages of rock failure process by acoustic parameters Rock and Soil Mechanics. (01):51-56
[3] Zhao M J, Wu D L 1999 Research on the relationship between acoustic parameters and stress of rock under uniaxial loading Chinese Journal of Rock Mechanics and Engineering. (01):51-55
[4] Liu X J, Liu H, Xu X L and Han L, 2009 Experimental study on acoustic propagation characteristics of sandstone with low porosity and low permeability under loading conditions Chinese Journal of Rock Mechanics and Engineering. 28(03):560-567
[5] Liang T C, Ge H K, Guo Z W and Song L L 2012 The damage state of rock is determined by acoustic emission and wave velocity variation Seismology in China. 28(02):154-166.
[6] Yan P, Zhang C, Gao Q D and Lu W B 2015 Variation of mechanical parameters of rock under different damage degree by acoustic wave test Rock and Soil Mechanics. 36(12):3425-3432.
[7] Li H R, Yang C H, Li B L and Yin X Y 2016 Study on acoustic emission characteristics and damage evolution law of salt rock under triaxial and multistage loading Journal of Rock Mechanics and Engineering. 35(04):682-691.
[8] Sun Q P, Zhang Z Z, Li P C and Sun Z Y 2019 Study on bedding effect and damage constitutive model of black shale under dynamic loading Chinese Journal of Rock Mechanics and Engineering. 38(07):1319-1331
[9] Li J H, Lian Y G, Ma Z C 2020 Loading rock mass damage acoustic response characteristics of the whole process and engineering significance to research Coal science and technology.: 1-7
[10] Wang L L 2010 Stress Wave Foundation 2nd Ed.Beijing: National Defense Industry Press.:5-64