Acta Technica 62 (2017), No. 6B, 445–456

Research of the impact of work stress wave characteristics of hydraulic jumbolter based on LS-DYNA

Xiaoyu Wang[1, 2]

Abstract. It analyzed wave mechanical model of hydraulic impact system,stress wave production,transfer and the impact energy when drill moving forward of hydraulic jumbolter. Established the three-dimensional model of tooth drill , the drill bit and the drill rod. Established finite element model MAT_JOHNSON_HOLM QUIST_CONCRETE of hydraulic impact rotating the jumbolter crashing rock-soil system based on LS-DYNA. Stimulated and analyzed the effect of impact power. The stimulations show that the stress wave and the impact energy were gradually decayed when drill moving forward. The results were consistent with the changes of the actual working condition, verifying the correctness and feasibility of the theoretical analysis of the effective simulation value, providing theoretical basis for impact characteristics research of hydraulic impactor.

Key words. Hydraulic impactor, Drill moving forward, Stress wave, Transfer, Impact power, Decay.

1. Introduction

As one key device for bolt support engineering construction, hydraulic bolt drill is widely applied to coal roadway, drive and rock-soil anchoring engineering construction. The key device of this equipment is hydraulic impactor. Its technical performance determines the advantages and disadvantages of the impact mechanical performance. Its working principle is that the hydraulic force drives the impact piston in the impactor to make reciprocating motion, impact the drill rod with piston and output the impact energy with the transmission of stress wave in the drill rod so as to realize the purpose of breaking the rock and soil.

The study on generation and transmission of stress wave during impact drilling

[1]College of Engineering, Xi'an International University, Shannxi Xi'an 710077 China

[2]College of Mechanical and Electrical Engineering,Xi'an University of Architecture and Technology ,Shannxi Xi'an 710077 China

and its influence on drilling effect can provide theoretical basis for study on hydraulic bolt drill impactor. Usually there are three kinds of methods to study the transient wave propagation in the solid under impact load: the first kind is the integral transform methods which takes the study on linear wave theory as the main study object, which are mainly used in areas like signal processing, defect detection and earthquake; the second kind is the method of characteristics taking the generalized characteristic theory as the instruction, which is mainly used in study on propagation of some waves; the third kind is the simulation of linear and nonlinear stress wave propagation with finite element analysis, which depends on proper constitutive model to get the simulation results of complicated problem, e.g. the study on high speed impact and machine shaping. The JH model proposed by T.J.Holmquist et al. in 1993 is used to describe the mechanical behaviors of the concrete under conditions of large deformation, high strain rate and high pressure. The third kind of method is adopted in this paper. Finite element JH concrete model is established based on use of LS-DYNA finite element software to simulate the stress wave generation, trasmisson and impact energy size during imapct drilling of hydraulic bolt drill in the concrete medium and analyze their influence on the drilling effect so as to build the theoratical foundation for study on hydraulic bolt drill impactor and provide initial study parameters [2].

2. Influence of stress wave generation, trasmisson and its influence on drilling effect during impact drilling

During operation of hydraulic bolt drill, the hydraulic cylinder and piston of the hydraulic drill are the source of power, the drill rod is the power transmission mechanism, and the drill bit breaking rock is the working mechanism. The force transferring mechanism of the impact bolt drill transmit the piston energy to the rock with the transmission of stress wave in the drill rod so as to realize the purpose of breaking the rock [3].

2.1. Generation of stress wave during impact drilling

During percussive rotary drilling of bolt drill, the energy produced by the impactor is the impact force which changes largely within extreme time. The impact force is transmitted to the rock through piston, bolt rod and bolt bit to break the rock in the form of stress wave. The generation and transmission of stress wave produces great effect on breaking the rock.

It is assumed that during percussive rotary drilling of bolt, the drill rod is one dimensional uniform section elastic rod with the stress on the section distributed evenly, the deformation when the drill rod is subject to force is neglected, and the drill rod makes longitudinal motion, as shown in Fig. 1. As for one rod unit with the length of dx, according to Newton's second law, we have[3]:

$$\rho A dx \frac{\partial^2 u}{\partial t^2} = -\frac{\partial F}{\partial x} dx - \mu \frac{\partial u}{\partial x} dx + XA dx\,. \tag{1}$$

Where, A is the section area of rod, m2; u is the axial displacement of the mass point in the rod, m; F is the force applied on the section area in the rod, N; $\rho$is the mateiral density, kg/$\tau_{ij}^{k}(t, t+1)$; X is the body force in direction x, N; and μ is the viscous damping coefficient around the unit length rod.

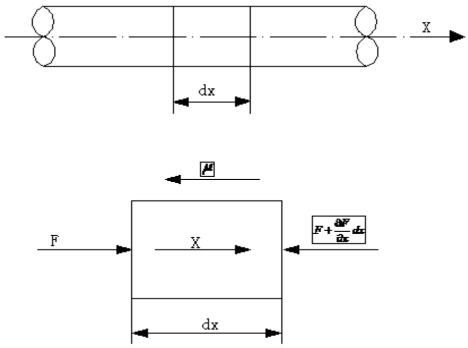

Fig. 1. Prismatic member unit

According to Hooke's law, the compressive stress and compressive strain are taken as positive and their relationship is [3]:

$$\sigma = -E\varepsilon \Leftrightarrow F = -AE\frac{\partial u}{\partial x}\,. \tag{2}$$

Where $\frac{\partial u}{\partial x}$ is the deformation rate of the drilling tool and E is the elastic modulus of the rod material, Pa

When the drill rod gravity and the viscous resistance on the surface around the drill rod are neglected, standard wave equation of one-dimensional elastic rod represented with displacement can be obtained according to formula (1) and (2) [4]:

$$\frac{\partial^2 u}{\partial t^2} = C^2\frac{\partial^2 u}{\partial x^2}\,. \tag{3}$$

Where: C is the propagation speed of longitudinal wave in the rock, m/s.

When the rod is of variable section, it is equivalent to (4) [4].

$$\begin{cases} \dfrac{\partial F}{\partial t} + AE\dfrac{\partial v}{\partial x} = 0\,, \\ \dfrac{\partial F}{\partial x} + \rho A\dfrac{\partial v}{\partial t} + \mu v - X = 0\,. \end{cases} \tag{4}$$

2.2. Stress wave propagation during impact drilling

The model formed by connection of many small rigid balls with mass and springs without mass is taken as the stress wave propagation model, as shown in Fig. 2.

When the first mall ball on the left is impacted, the first left spring is compressed to push the second ball to move whose motion compresses the second left spring.

It goes like this, the small ball moves to compress the spring which pushes the ball to move. The inertia of small ball and the elasticity of the spring transfer mutually and they are entirety mutually to form the transfer of force and speed in the object. This form is the stress wave propagation. The wave propagation involves the transfer of disturbance (mass point state) whose strength and shape depend on the characteristics of the load (seismic source) and it is characterized by superposition, propagation and transmissivity[5].

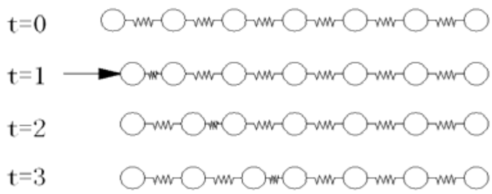

Fig. 2. The Stress wave with quality and elastomer ransfer model

2.3. *Influence of incident wave shape on the bolt drilling effect*

During impact drilling, many times of stress cycles are produced in the drill rod each tiem the drill rod tail is impacted by the piston. When the drill rod does not contact the rock, the stress wave makes many times of reciprocating reflection in the rod so that the drill rod can impact the drilling bottom and then the stress amplitude starts to decrease. When the disturbance produced by teh stress wave propagates in the drill rod, it attenuates due to internal and external friction. Set the attenuation rate to be β each time the disturbance is transmitted via unit length and the attenuation amplitude from X to $X + \Delta X$ is:

$$\sigma = \sigma_0 e^{-\beta X} \,. \tag{5}$$

Where, σ_0 the disturbance stress amplitude before attenuation at $X = 0$. The attenuation rate β is constant; when β is measured in practice, the disturbance is used to make many times of free reflections at two rod ends in the long rod and then the amplitude is measured. The attenuation rate β is represented as:

$$\beta = \frac{1}{2nl} \ln\left(\frac{\sigma_0}{\sigma_n}\right) \,. \tag{6}$$

3. Modeling of impact rock-drilling system based on LS-DYNA

3.1. Building of impact rock-drilling system model based on LS-DYNA

(1) Finite element modeling and material parameter definition during impact drilling

Based on previous theoretical analysis, LS-DYNA finite element analysis software is used to make modeling and dynamic simulation of impact drilling system of certain rotary impact type of hydraulic bolt drill and the initial kinetic energy that the drill bit shall have when the drill bit with 120 mm of diameter impacts the granite of class 10 of Protodyakonov scale to break the rock is obtained. Based on such purpose and calculation convenience and feasibility, some simplification is made for the model built: 3D modeling of impact piston is neglected, and 3D modeling of rock, drill tooth, bit and drill rod is made; the stress wave produced by the impact piston colliding with drill rod tail is changed to stress wave produced when the drill tail end face is subject to external force; the drill tail and drill rod are addressed together [3].

(2) Modeling of drill rod and bit

According to actual working conditions of impact drilling and available products of rotary impact type of hydraulic bolt drill, hollow drill rod with hollow section is adopted. The specific size is: total length of drill rod of 3000 mm, inner diameter of 60 mm, outer diameter of 80 mm; rear end length of drill bit of 100 mm, half of which is set on the drill rod, inner diameter of 80 mm and outer diameter of 90 mm; the front end length of the drill bit is 150 mm and the physical body diameter is 120 mm, as shown in Fig. 3; the drill bit has flat bottom. The drill teeth are spherical ones distributed as per even force principle, four cycles in total from the inner cycle to the outer cycle and the tooth number is 15, 12, 3 and 1 respectively, 31 teeth in total, as shown in Fig. 4; the water hole diameter at the front end of the drill bit is 10 mm, the spherical tooth diameter is 10 mm. The drill rod, bit and tooth modeling parameters are shown in Tab. 1[3].

Table 1. Rock material parameters

Name	drill rod	drill bit	Ball gear
Material	Low alloy steel Q345	Quenched and tempered steel 20Ni4Mn	YG8
Material characteristics	Linear elastic body		
Density	7.85 g/cm3	7.95 g/cm3	14.5 g/cm3
Modulus of elasticity	206GPa	218GPa	588GPa
Poisson's ratio	0.3	0.3	0.22

(3) Modeling of rock

It is pointed out in literature [8–10] that the rock breaking process of the rock material consists of five stages such as rock elastic deformation, plastic deformation,

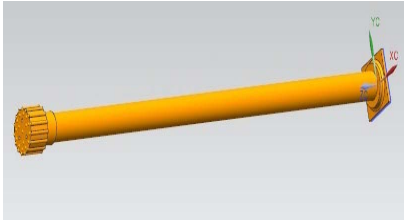

Fig. 3. The drill rod 3D graph

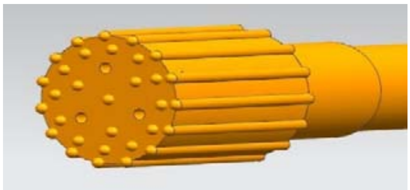

Fig. 4. The drill bit 3D graph

rock failure and breaking, tensile breaking and shear breaking. When the impact load is large, the rock firstly experiences compressive stress breaking together with large quantity of micro-cracks and fissures around the broken pits; secondly the cracks rapidly grow and expand with the action of tensile stress; finally the drill bit rotates to shear the rock to form the broken pits. When the rock experiences plastic deformation, the stress and strain meet the general Hooke's law. When the rock breaking enters the second stage, the stress and strain do not meet such law again, so only the relationship between increments of these two has to be established and taken as the research object. The strain increment is divided into elastic strain increment and plastic strain increment for consideration [6–10].

Due to the work object of the bolt drill and its universality, MAT_JOHNSON_HOLM QUIST_CONCRETE concrete model is selected in this paper to simulate the concrete and rock with high strain rate and large deformation. The material yield of H-J-C model meets formula (7) [1, 3, 6–13].

$$\sigma^* = \left[A\,(1-D) + BP^{*N}\right](1 + C\ln\varepsilon^*)\ . \tag{7}$$

Where A is the dimensionless viscous constant; D is the material damage constant; B is dimensionless pressure enhancement coefficient; N is dimensionless pressure enhancement index, C is the strain rate coefficient and ε is engineering strain.

(4) Grid division and load and constraint addition

Firstly SOLID164, 8 node hexahedron unit is used to divide the grid for impact mechanical system. The cross section of drill rod in circumferential direction is divided into four equal amounts in the diameter direction. The concrete slab model adopts the division size of Global 0.0025 and standard hexahedron grid scanning is used. As for the drill bit, the drill teeth contacting the rock and its nearby cells are refined and the drill rod part is coarsened to get accurate simulation results[5–7].

The type of contact between drill teeth and the concrete is defined to be face-to-face erosion contact (ESTC) and the constraint connection between the drill teeth and the bid is rigid. The instantaneous load is applied to the drill rod tail end face. The concrete bottom is the fixed end and full constraint is performed. The front end face of the bolt is shown in Fig. 5 and Fig. 6 and the overall impact system grid is shown in Fig. 7.

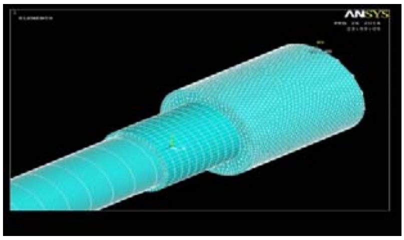

Fig. 5. The anchor modeling diagram

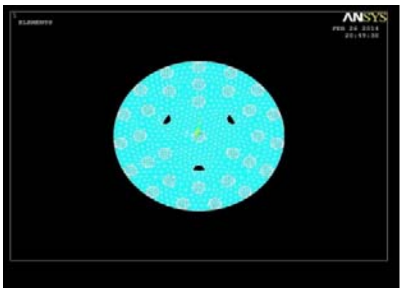

Fig. 6. The Front end face model diagram of bolt

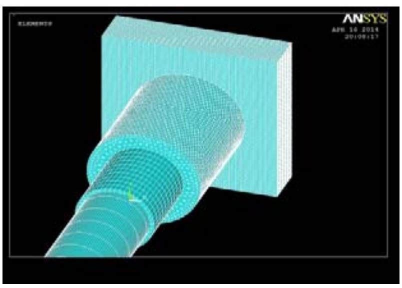

Fig. 7. The overall impact system mesh map

4. Analysis of stress wave propagation simulation

The stress wave is attenuated gradually during propagation in the drill rod due to the internal and external friction, as shown in Fig. 8 $\sim$ 11 which indicate the stress of the stress wave from the drill rod to the drill bit at four different moments and parts.

Fig. 8 shows that during initial drilling, the external impact load applied to the bolt is 863 MPa; Fig. 9 shows that with the gradual increase of the impact energy, the external impact load at this time reaches the maximum, being 998 MPa; Fig. 10 shows that the external impact load withstood by the bolt starts to decrease, being 763 MPa; Fig. 11 shows that the external impact load reduces to the minimum, being 618 MPa. The law of external impact load withstood by the bolt varying with time meets the law of change of impact load in literature [5] (during impact drilling) and it is the same as the actual operation condition, so the simulation value is valid and feasible.

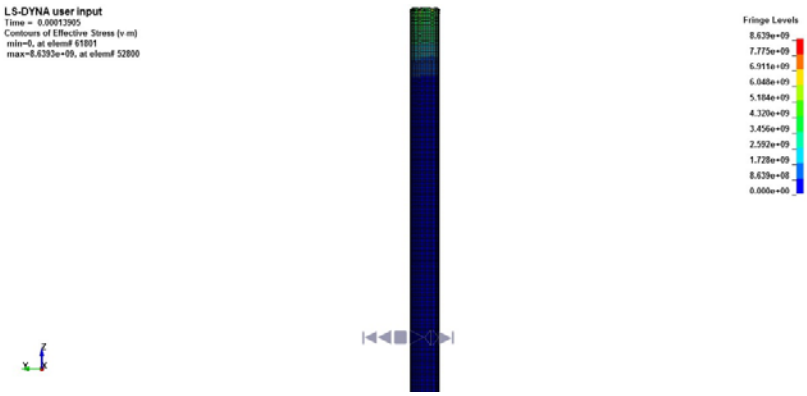

Fig. 8. The stress wave propagation in the drill rod (1)

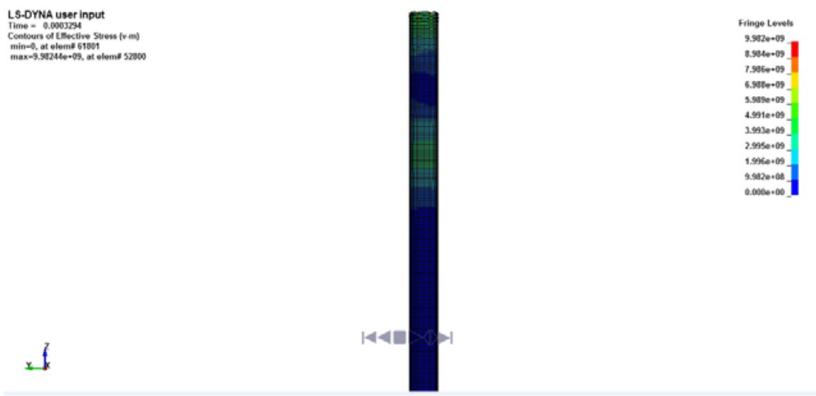

Fig. 9. The Stress wave propagation in the drill rod (2)

As shown in the figure, with the action of impact load, the stress wave propagates in the drill rod in the form of pulse. The stress wave starts to attenuate with the increase of propagation distance, but the attenuation value is limited and it is not obvious. Besides, due to external and internal friction, the stress wave experiences certain diffusion and the boundary between one impact and another impact becomes smaller and smaller, i.e. the deep blue area between peaks becomes increasingly

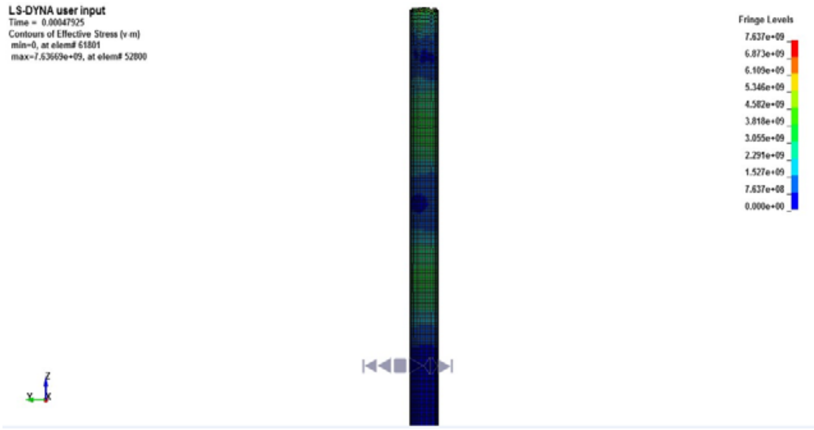

Fig. 10. The Stress Wave Propagation in the Drill Rod (3)

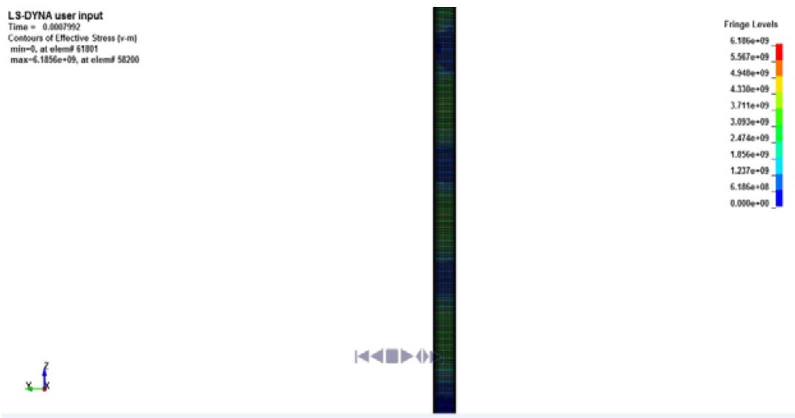

Fig. 11. The stress wave propagation in the drill rod (4)

small, which indicates the energy diffusion.

It is pointed out in literature [3] and [5] that the attenuation rate η of the stress wave in the drill rod is about 0.2%. According to Fig. 8~11, the attenuation rate η calculated is about 0.23% per meter, so this rate when the stress wave propagates in the drill rod can be neglected.

Fig. 12 shows the kinetic energy curve simulation when the drill bit (with drill rod) impacts the rock. The initial kinetic energy is about 500 J when the drill bit impacts the rock. The maximum value of the impact energy is about 720 J and the minimum value is about 430 J and the impact energy value fluctuates in the region. During the impact, the incident wave and the reflection wave are superimposed, which increases the kinetic energy of the drill bit and leads to the fluctuation change as well. With the deepening of the drill, the impact energy starts to decrease and it decreases to the minimum after about 3 ms and the corresponding impact energy is about 140 J. The rock runs into brittle fracture damage after elastic deformation during such process. At the later period of the drilling, when the impact energy decreases to the extent where it is impossible to break the rock, the drill bit will rebound. The calculation results are the same as the theoretical estimation [3].

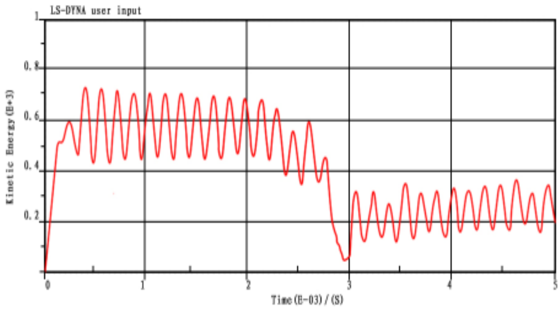

Fig. 12. Bit shock energy and time curve

5. Conclusions

The stress wave generation, transmission and influence of impact energy on the drilling effect are studied during impact drilling of bolt drill. LS-DYNA finite element analysis software is used to establish the finite element model for impact rock breaking system to make simulation and analysis of the stress wave propagation and impact energy withstood by the drill bit. The results are consistent with the actual working conditions, which indicates that the research method in this paper is feasible, thus providing theoretical basis for study on rotary type of hydraulic bolt drill impactor.

Acknowledgement

Shaanxi science and technology project (No. 2011K 10-18); Shaanxi Provincial Department of education special research project (No. 09JK559).

References

[1] Holmquist T J, Johnson G R: (1993) *A computational constitutive model for concrete subjected to large strains, high strain rates, and high pressure* [A].14th International Symposium on Ballistics[C].Quebec, Canada:[s.n.],1993:591-600.

[2] Zhou You, Li Guo-shun, Tang Jin-yuan: (2011) *Simula-tion and analysis for pick cutting rock by LS_DYNA* [J]. Journal of Engineering Design, 18(02):104-110.

[3] Zhu Hai-yan, Liu Qing-you, Deng Jin-gen: (2012) *Rockbreaking Mechanism of Rotary-percussive Drilling*[J]. Journal of Basic Science and Engineering, 20(04):622-631.

[4] Rong Yao, Xu Xi-bing, Zhao Ming-jie: (2006) *The numerical simulation propaga-*

tion of stress waves in the county rock with bolting[J].ChineseJournal of Underground Space and Engineering, 02(01):115-119.

[5] Hua J, Mi G C: (2014) *Aircraft impact analysis of nuclear safety-related concrete structures: A review*[J]. Engineering Failure Analysis, 46:118-133.

[6] Reutterer T, Hahsler M, Hornik K: (2015) *Data Mining und Marketing am Beispiel der explorativen Warenkorbanalyse*[J]. Marketing Zeitschrift Für Forschung Und Praxis, 29(3):163-179.

[7] Reutterer T, Hahsler M, Hornik K: (2015) *Data Mining und Marketing am Beispiel der explorativen Warenkorbanalyse*[J]. Marketing Zeitschrift Für Forschung Und Praxis, 29(3):163-179.

[8] Li K, Zhong Z: (2006) *Fast statistical spam filter by approximate classifications*[C]// Joint International Conference on Measurement and Modeling of Computer Systems, Sigmetrics/performance 2006, Saint Malo, France, June. DBLP, 2006:347-358.

[9] Prather C M, Pelini S L, Laws A, et al.: (2013) *Invertebrates, ecosystem services and climate change.*[J]. Biological Reviews, 88(2):327-348.

[10] Gama B A, Bogetti T A, Fink B K, et al. :(2001) *Aluminum foam integral armor: a new dimension in armor design*[J]. Composite Structures, 52(3):381-395.

[11] Micheler A, Pietsch I, Lochmann E R: (1973) *Über die RSN-Synthese bei Saccharomyces-Zellen nach photodynamischer Behandlung und nach Röntgenbestrahlung*[J]. Radiation and Environmental Biophysics, 10(3):249-256.

Received May 7, 2017