Experimental Study of the Dynamic Shear Modulus Ratio and Damping Ratio of the Quaternary Sedimentary Soils in the Offshore Areas of the Yellow Sea

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The effects of marine and continental sedimentary environments and geological ages on the dynamic shear modulus ratio and damping ratio of the Quaternary sedimentary soils in the offshore areas of the Yellow Sea were analyzed by using a resonant column device (GCTS, USA). The results show the following: (1) The $G_{\text{max}}$ of various marine soils increases with the depth and shows a typical linear relationship. (2) The marine transgression has significantly different effects on the dynamic shear modulus ratio versus the shear strain amplitude curves (i.e., $G/G_{\text{max}} \sim \gamma_a$ curves) and the damping ratio versus the shear strain amplitude curves (i.e., $\lambda \sim \gamma_a$ curves) of the different soil types in the offshore areas of the Yellow Sea. The effects of marine transgression were strong on clays, moderate on silty clays, and minor on silts. (3) The geological ages have noticeable effects on the $G/G_{\text{max}} \sim \gamma_a$ curves of the tested marine silty clays, marine silts, and continental silty clays, but the effects of geological ages on the $\lambda \sim \gamma_a$ curves are minimal. The fitting parameters and recommended empirical equations of the $G/G_{\text{max}} \sim \gamma_a$ and $\lambda \sim \gamma_a$ curves for each type of the tested soils (silty clay, clay, and silt) were obtained mirroring the effects of sedimentary environments and geological ages.

1. Introduction

The 21st century is widely considered to be the era of the ocean. All of the coastal countries have placed a higher priority on the ocean within their overall framework of national development. China has a very long coastline of more than 18,000 km, and thus, China has successively proposed marine strategic plans such as the Belt and Road and the Yellow Sea Economic Circle. In particular, the Yellow Sea and its coastal areas are experiencing intensive planning and construction of a large number of offshore traffic projects and marine projects. The Yellow Sea and its coastal areas are located in the North China Seismic Zone, which has complex seismic geological structures and is frequently subject to seismic activity, including a magnitude 6 earthquake in the Yellow Sea in 1764, a magnitude 6.5 earthquake in the Yellow Sea in 1764, and a far-field magnitude 8.5 earthquake in Tancheng in 1668. There may be Late Pleistocene faults and Holocene faults in the zone, which increase the possibility of destructive earthquakes in the future. The offshore areas of the Yellow Sea contain a thick Quaternary sedimentary sequence, which is comprised of soft soils. These soils are mainly marine plains dominated by cohesive soils and saturated sandy soils. The strong earthquakes that occur in this area may lead to a significant site amplification effect and result in the subsidence of soft soil or liquefaction of sandy soil in these areas, which poses a serious threat to the safety of major engineering structures and the performance of socioeconomic activities.

The variation of the dynamic shear modulus ratio $G/G_{\text{max}}$ and the damping ratio $\lambda$ against the shear strain amplitude $\gamma_a$ directly reflects the nonlinear and hysteretic characteristics of the stress-strain relationship of soils under...
2. Engineering Geological Conditions of the Study Region

The study area is located near the coast of the Yellow Sea, and most parts of the region are less than 5 m above sea level, falling in the category of a coastal marine plain. The Quaternary sediments in the region are more than 200 m thick and have experienced marine transgression five times since the late Early Pleistocene. With the formation of fluvi-al, lacustrine, and marine deposits alternately, broad coastal facies and alluvial facies with soft clay layers and saturated sand layers have been formed.

According to the chronological order of strata, the characteristics of soil sedimentary structure are as follows:

1. During the Holocene period, the stratum was buried at a depth of 8-25 m, mainly composed of tidal flat facies of clay, clay interbedded with silt, silt and clay interbedded, and gray clay
2. In the Late Pleistocene, the stratum was buried at a depth of 16-21 m, mainly composed of gray clay and silt flooding facies and gray lacustrine deposits
3. In the early Late Pleistocene, the stratum was buried at a depth of 28-42 m, mainly composed of tidal flat facies of gray clay, clay intercalated with silt sand, clay silt sand, and gray clay supertidal zone deposits
4. In the late Middle Pleistocene, the stratum was buried 40-55 m deep and 7-20 m thick. The lower part mainly was composed of flooding facies and high tide flats, and the upper part was composed of lacustrine facies
5. In the early mid-Pleistocene, the stratum was buried 70-106 m deep and 25-60 m thick. The lower part was composed of gray clay lagoon facies and tidal flat facies, partially with gray-green fine sand in riverbed facies and gray silt delta facies, and the upper part was composed of tidal flat facies and shallow ocean facies with gray clay and silt sand

The sedimentary environments and geological ages of the soils have a significant impact on their dynamic deformation characteristics. The soil samples were identified based on their colors and the existence of shells, calcareous nodules, and iron-manganese oxides. The identifications in conjunction with the comparison between the borehole logs and the relevant geological maps account for the classification of soil categories, sedimentary facies, and geological ages of the tested samples. The classification, summarized in Table 1, reveals that there are 19 clayey soil samples in the shallow layers, within 100 m below the surface. 75% of the silt samples are mainly deposited in the Pleistocene, which is attributed to the fact that the seawater in the marine transgression carried a large amount of granular soils from the rivers, lakes, and marine facies into the flat areas where separation and sedimentation took place. The Holocene silt sand samples are mainly deposited in the marine facies. The silty clay samples from both the marine and continental
| Number | Lithology      | Depth, \( h \) (m) | Consolidation pressure, \( \sigma \) (kPa) | Density, \( \rho \) (g/cm\(^3\)) | Moisture content, \( \omega \) (%) | Void ratio, \( e \) | State |
|--------|----------------|---------------------|---------------------------------------------|---------------------------------|-------------------------------|-----------------|-------|
| 1      | Silty clay     | 51.7-52.0           | 345                                         | 2.09                            | 22.77                         | 0.53            | CL    |
| 2      | Clay           | 80.7-81             | 540                                         | 2.10                            | 30.75                         | 0.70            | ML    |
| 3      | Silty clay     | 3.7-4.0             | 50                                          | 1.85                            | 34.46                         | 0.91            | CH    |
| 4      | Silty clay     | 17.0-17.3           | 115                                         | 1.95                            | 33.14                         | 0.81            | CL    |
| 5      | Silty clay     | 21.5-21.8           | 145                                         | 1.87                            | 27.03                         | 0.77            | CL    |
| 6      | Clay           | 39.8-40             | 265                                         | 1.96                            | 29.53                         | 0.79            | CL    |
| 7      | Silty clay     | 50.1-50.3           | 335                                         | 2.02                            | 23.44                         | 0.63            | CL    |
| 8      | Silty clay     | 54.5-54.3           | 360                                         | 1.94                            | 27.53                         | 0.72            | CL    |
| 9      | Clay           | 79.8-80.0           | 535                                         | 2.06                            | 23.40                         | 0.55            | CL    |
| 10     | Clay           | 94.6-94.8           | 635                                         | 2.01                            | 29.50                         | 0.69            | CL    |
| 11     | Silty clay     | 3.0-3.3             | 50                                          | 1.84                            | 30.79                         | 0.90            | CH    |
| 12     | Silty clay     | 17.0-17.3           | 115                                         | 1.81                            | 33.38                         | 0.95            | CL    |
| 13     | Silty clay     | 18.7-19.0           | 125                                         | 1.96                            | 29.73                         | 0.79            | CL    |
| 14     | Silty clay     | 17.05-17.25         | 115                                         | 2.06                            | 25.87                         | 0.60            | CL    |
| 15     | Clay           | 34.05-34.25         | 230                                         | 2.13                            | 24.54                         | 0.52            | CL    |
| 16     | Clay           | 44.05-44.25         | 295                                         | 2.03                            | 25.74                         | 0.74            | CL    |
| 17     | Silty clay     | 54.05-54.25         | 360                                         | 2.03                            | 22.03                         | 0.57            | CL    |
| 18     | Clay           | 76.85-77.05         | 515                                         | 1.99                            | 26.56                         | 0.70            | ML    |
| 19     | Silty clay     | 17.2-17.4           | 115                                         | 2.11                            | 24.89                         | 0.58            | CL    |
| 20     | Silty clay     | 23.5-23.7           | 160                                         | 1.89                            | 33.97                         | 0.93            | CH    |
| 21     | Clay           | 27.6-27.8           | 185                                         | 2.14                            | 23.55                         | 0.50            | CL    |
| 22     | Silty clay     | 40.2-40.4           | 270                                         | 1.98                            | 24.34                         | 0.68            | CL    |
| 23     | Clay           | 77.3-77.5           | 515                                         | 2.03                            | 25.56                         | 0.64            | CL    |
| 24     | Clay           | 97.8-98             | 655                                         | 2.12                            | 27.36                         | 0.63            | ML    |
| 25     | Silty clay     | 33.7-34             | 225                                         | 1.95                            | 40.32                         | 0.92            | CL    |
| 26     | Clay           | 71.8-72             | 480                                         | 2.09                            | 29.78                         | 0.66            | ML    |
| 27     | Clay           | 78.7-79             | 525                                         | 2.13                            | 24.91                         | 0.58            | ML    |
| 28     | Silty clay     | 5.8-6              | 50                                          | 1.84                            | 38.55                         | 0.94            | CH    |
| 29     | Silty clay     | 12.8-13             | 85                                          | 1.91                            | 33.45                         | 0.88            | CL    |
| 30     | Clay           | 35-35.3             | 235                                         | 1.95                            | 21.59                         | 0.67            | CL    |
| 31     | Silty clay     | 40-40.3             | 270                                         | 1.94                            | 26.84                         | 0.72            | CL    |
| 32     | Silty clay     | 47.7-48             | 320                                         | 1.98                            | 25.87                         | 0.72            | CL    |
| 33     | Silty clay     | 57.7-58             | 385                                         | 1.98                            | 25.51                         | 0.68            | CL    |
| 34     | Clay           | 64-64.3             | 430                                         | 1.96                            | 38.04                         | 0.85            | ML    |
| 35     | Clay           | 79-79.3             | 530                                         | 2.01                            | 26.76                         | 0.68            | ML    |
| 36     | Clay           | 83-83.3             | 555                                         | 1.99                            | 27.45                         | 0.69            | ML    |
| 37     | Clay           | 86.4-86.7           | 580                                         | 2.03                            | 25.56                         | 0.66            | CL    |
| 38     | Clay           | 89.7-90             | 600                                         | 2.06                            | 20.46                         | 0.57            | ML    |
| 39     | Clay           | 92.7-93             | 620                                         | 2.10                            | 21.76                         | 0.55            | ML    |
| 40     | Silty clay     | 4.4-2              | 50                                          | 1.87                            | 34.54                         | 0.84            | CL    |
| 41     | Silt           | 14.8-15             | 100                                         | 1.96                            | 30.56                         | 0.81            | Medium|
| 42     | Silty clay     | 30-30.2             | 200                                         | 1.97                            | 22.56                         | 0.66            | ML    |
| 43     | Silt           | 36.8-37             | 245                                         | 2.01                            | 29.45                         | 0.70            | Dense |
| 44     | Silt           | 42.8-43             | 285                                         | 1.99                            | 30.12                         | 0.75            | Dense |
| 45     | Silt           | 50.8-51             | 340                                         | 2.03                            | 28.15                         | 0.69            | Dense |
| 46     | Silty clay     | 70-70.2             | 470                                         | 2.10                            | 23.56                         | 0.59            | ML    |
| 47     | Silty clay     | 78-78.2             | 520                                         | 1.99                            | 23.45                         | 0.68            | ML    |
| 48     | Silt           | 86.6-87             | 580                                         | 2.06                            | 28.23                         | 0.67            | Dense |

Table 1: Basic physical properties of undisturbed soil.
facies were primarily deposited in the Holocene and Pleistocene.

3. Soil Sampling and Testing

3.1. Soil Sampling. A total number of 89 undisturbed soil samples were collected from 14 boreholes in the coastal area of the Yellow Sea by using the in situ soil tube method. The depth of soil samples are from 0 to 100 m. As shown in Figure 1, the borehole sites were distributed close to each other so as to reveal the dynamic characteristics of the soils in more detail. Each undisturbed soil sample was prepared into a solid cylindrical shape specimen with the diameter of 50 mm and the height of 100 mm.

| Number | Lithology | Depth, h (m) | Consolidation pressure, $\sigma$ (kPa) | Density, $\rho$ (g/cm$^3$) | Moisture content, $\omega$ (%) | Void ratio, $e$ | State |
|--------|-----------|--------------|----------------------------------------|--------------------------|-------------------------------|----------------|-------|
| 49     | Silty clay| 93-93.2      | 620                                    | 2.08                     | 23.76                         | 0.59           | ML    |
| 50     | Silt      | 5.5-5.7      | 50                                     | 1.93                     | 31.67                         | 0.81           | Medium |
| 51     | Silty clay| 11.5-11.7    | 80                                     | 1.96                     | 24.56                         | 0.70           | CL    |
| 52     | Silt      | 22-22.2      | 150                                    | 1.98                     | 29.98                         | 0.79           | Medium |
| 53     | Silty clay| 32-32.2      | 215                                    | 1.96                     | 23.45                         | 0.66           | ML    |
| 54     | Silt      | 54-54.2      | 360                                    | 1.99                     | 29.23                         | 0.76           | Dense |
| 55     | Silty clay| 77-77.2      | 515                                    | 2.03                     | 24.87                         | 0.62           | ML    |
| 56     | Silt      | 88-88.2      | 590                                    | 2.02                     | 30.21                         | 0.73           | Dense |
| 57     | Silty clay| 96-96.2      | 640                                    | 2.08                     | 21.87                         | 0.55           | ML    |
| 58     | Silty clay| 7.7-7.2      | 50                                     | 1.86                     | 32.76                         | 0.89           | CL    |
| 59     | Silt      | 13-13.2      | 90                                     | 1.94                     | 28.23                         | 0.81           | Medium |
| 60     | Silty clay| 21.5-21.7    | 145                                    | 1.95                     | 27.89                         | 0.71           | CL    |
| 61     | Silty clay| 35-35.2      | 235                                    | 2.04                     | 23.87                         | 0.63           | ML    |
| 62     | Silt      | 45.5-45.7    | 305                                    | 2.05                     | 29.87                         | 0.70           | Dense |
| 63     | Silty clay| 63.5-63.7    | 425                                    | 2.03                     | 21.89                         | 0.62           | ML    |
| 64     | Silt      | 80-80.2      | 535                                    | 2.02                     | 26.97                         | 0.72           | Dense |
| 65     | Silty clay| 98.5-98.7    | 660                                    | 2.11                     | 20.21                         | 0.56           | ML    |
| 66     | Silty clay| 8-8.2        | 55                                     | 1.92                     | 31.98                         | 0.79           | CL    |
| 67     | Silt      | 18.8-19      | 125                                    | 1.98                     | 32.87                         | 0.80           | Medium |
| 68     | Silty clay| 30-30.2      | 200                                    | 1.96                     | 19.87                         | 0.61           | ML    |
| 69     | Silt      | 40.8-41      | 275                                    | 1.97                     | 29.76                         | 0.77           | Dense |
| 70     | Silt      | 57-57.2      | 380                                    | 2.00                     | 26.89                         | 0.73           | Dense |
| 71     | Silt      | 68.8-69      | 460                                    | 2.01                     | 28.98                         | 0.73           | Dense |
| 72     | Silt      | 83.8-84      | 560                                    | 2.04                     | 27.12                         | 0.70           | Dense |
| 73     | Silty clay| 92-92.2      | 615                                    | 2.11                     | 18.12                         | 0.53           | ML    |
| 74     | Silt      | 5.8-6.0      | 50                                     | 1.98                     | 33.80                         | 0.81           | Medium |
| 75     | Silty clay| 11-11.2      | 75                                     | 1.95                     | 24.21                         | 0.69           | CL    |
| 76     | Silt      | 21.8-22      | 145                                    | 1.97                     | 30.12                         | 0.77           | Medium |
| 77     | Silty clay| 35-35.2      | 235                                    | 1.95                     | 29.87                         | 0.77           | Medium |
| 78     | Silty clay| 44-44.2      | 295                                    | 1.98                     | 25.12                         | 0.69           | CL    |
| 79     | Silt      | 52.8-53      | 355                                    | 1.99                     | 28.98                         | 0.74           | Dense |
| 80     | Silty clay| 74-74.2      | 495                                    | 2.01                     | 19.21                         | 0.61           | ML    |
| 81     | Silty clay| 93-93.2      | 620                                    | 2.01                     | 20.21                         | 0.60           | ML    |
| 82     | Silty clay| 9-9.2        | 60                                     | 1.89                     | 31.23                         | 0.85           | CL    |
| 83     | Silty clay| 27-27.2      | 180                                    | 1.93                     | 24.32                         | 0.71           | CL    |
| 84     | Silty clay| 37-37.2      | 250                                    | 1.99                     | 25.21                         | 0.67           | ML    |
| 85     | Silty clay| 47-47.2      | 315                                    | 1.96                     | 25.90                         | 0.70           | CL    |
| 86     | Silty clay| 58.5-58.7    | 390                                    | 2.03                     | 21.23                         | 0.60           | ML    |
| 87     | Silty clay| 70-70.2      | 470                                    | 2.07                     | 23.21                         | 0.62           | ML    |
| 88     | Silty clay| 83.5-83.7    | 560                                    | 2.12                     | 21.32                         | 0.55           | ML    |
| 89     | Silty clay| 98-98.2      | 655                                    | 2.11                     | 22.87                         | 0.58           | ML    |
3.2. Resonant Column Testing. The testing was conducted using the TSH-100 high-precision fixed-free resonant column device (GCTS, USA) at the Institute of Natural Disaster Prevention and Control of the Ministry of Emergency Management (Figure 2). The torque (or rotation) and the cell pressure are controlled independently by the apparatus. The consolidation pressure is provided by a pneumatic servo system, and a fully automated floating torsional drive is attached to excite at the top of the samples.

First, the soil was made into a solid cylindrical sample with a diameter of 50 mm and a height of 100 mm. Isotropic consolidation was conducted after the soil specimen was installed into the test apparatus, with a membrane filmed outside it. The effective confining pressure was determined according to the depth of the soil layer. The durations of the consolidation are more than 3 hours and 12 hours for cohesionless soils and cohesive soils, respectively. After consolidation, resonant column testing was conducted by applying the multistage frequency sweeping excitation on the top of the specimen following ASTM D4105-92 to measure the shear modulus $G$ and damping ratio $\lambda$ in the shear strain range of $10^{-6}$ to $10^{-3}$. The schemes of the resonant column tests, specifically the index properties of the specimens and the corresponding effective confining pressures, are listed in Table 1.

4. Testing Results and Analysis

Since the sedimentary environment and geological age of the soils have a significant impact on their dynamic shear modulus ratios and damping ratios, the soil samples were observed to determine their colors and whether or not they contained shells, calcareous nodules, and/or iron-manganese oxides. The observations were made in conjunction with the comparative analysis of the borehole logs and the relevant geological maps in order to categorize the soil samples based on their soil properties, sedimentary facies, and geological ages. The results (Table 2) revealed that there were many clayey soils in the shallow layers within 100 m of the surface, while the silt samples were mainly deposited in the Pleistocene, which is attributed to the fact that the seawater in the marine transgression carried a large amount of gravel soils from the rivers, lakes, and marine facies into the flat areas where separation and sedimentation took place. In contrast, the silty clay samples from both the marine and continental facies were primarily deposited in the Holocene and Pleistocene. The Holocene clay samples were mainly deposited in the marine facies.

Figure 3 shows the typical results of the resonant column test. The strain amplitude of the sample under different excitation frequencies is shown in Figure 3(a). The resonance frequency $f_1$ of the sample $\gamma_a$ at the maximum under the
corresponding excitation load can be obtained. At the resonance frequency, the strain time history of the sample is shown in Figure 3(b). Under free vibration, the strain time history of the sample is shown in Figure 3(c).

4.1. Change of $G_{\text{max}}$ with Depth. As an important parameter for evaluating the dynamic characteristics of soil and characterizing the maximum elastic stiffness of soil, the maximum dynamic shear modulus $G_{\text{max}}$ is usually defined as $G$ when $\gamma_s \leq 10^{-6}$. According to the hyperbolic relationship between soil dynamic modulus and dynamic strain under small vibration proposed by Hardin and Drnevich [18], the linear relationship between $1/G$ and $\gamma_s$ can be obtained as $1/G = a + b\gamma_s$. And then, the hyperbolic model ($\gamma_s \rightarrow 0$) between $1/G$ and shear strain $\gamma_s$ can be used to obtain the maximum dynamic shear modulus $G_{\text{max}}$ of marine soil.

$$G_{\text{max}} = \lim_{\gamma_s \to 0} \frac{1}{a + b\gamma_s}.$$  (1)

The TSH-100 resonant column test system developed by the GCTS company can measure the dynamic shear modulus $G$ of the soil in the range of $10^{-6} \sim 10^{-3}$. Equation (1) can be used to obtain the $G_{\text{max}}$ of marine soil at different depth ranges from 15 to 140 MPa.

Figure 4 shows the $G_{\text{max}}$ values of various marine soils and their changes with depth. It can be seen that the $G_{\text{max}}$ of various marine soils increases with the depth and shows a typical linear relationship. The prediction relationship between $G_{\text{max}}$ and depth can be expressed as $G_{\text{max}} = 15.37 \times h + 1.13$. The $h$ represents the depth of the sample, and its unit is m.

4.2. Effects of the Sedimentary Environment on the $G/G_{\text{max}}$ ~ $\gamma_s$ and $\lambda$ ~ $\gamma_s$ Curves. The three-parameter Martin-Davidenkov model was adopted to investigate the variation characteristics of dynamic shear modulus ratio $G/G_{\text{max}}$ against the shear strain amplitude $\gamma_s$ of the tested soils since it has been proven to fit experimental data well for soil samples in Jiangsu province, China [5]. The model is expressed as

$$\frac{G}{G_{\text{max}}} = 1 - \left[ \frac{(\gamma/\gamma_0)^{2B}}{1 + (\gamma/\gamma_0)^2A} \right].$$  (2)

Here, $A$, $B$, and $\gamma_0$ are the best-fitting parameters. In particular, in the case of $A = 1$ and $B = 0.5$, the Martin-Davidenkov model simplifies to the H-D hyperbolic model [19], where $\gamma_0$ denotes the reference shear strain and is equal to the shear strain values when $G/G_{\text{max}} = 0.5$ [20].

The damping ratio versus shear strain amplitude ($\lambda$ ~ $\gamma_s$) curves of each tested specimen were fitted and analyzed using the following empirical Equation (3) proposed by Chen et al. [5]:

$$\lambda = \lambda_{\text{min}} + \lambda_0 \times \left( 1 - \frac{G}{G_{\text{max}}} \right)^\beta.$$  (3)

Here, $\lambda_{\text{min}}$ is the basic damping ratio of a soil sample under a very small strain, which is related to the soil properties and consolidation state. $\lambda_0$ and $\beta$ are the shape coefficients of the $\lambda$ ~ $\gamma_s$ curve.

![Table 2: Classification and the corresponding number of the tested soil samples.](image)

| Lithology   | Sedimentary environment | Geological age | Holocene | Pleistocene |
|-------------|-------------------------|----------------|----------|------------|
| Silt clay   | Marine                  | 11             | 15       |
|             | Continental             | 6              | 19       |
| Silt sand   | Marine                  | 5              | 9        |
|             | Continental             | 0              | 6        |
| Clay        | Marine                  | 0              | 9        |
|             | Continental             | 0              | 10       |

![Figure 2: TSH-100 resonant column testing system.](image)
sedimentary environments on the
within the working range of the shear strain (10^{-6})
the resonant column device, the
fore, they exhibit stronger nonlinearity. For Pleistocene clays,
muddy silty clay deposited during the Holocene, and there-
the fact that the marine silty clays were dominated by
continental silty clays. This is mainly attributed to
silty clays have similar
curves of the marine silty clays are slightly lower than those
λ~γ_a curves for the various types of soils. For Holocene silty clays,
those of the continental clays, while the
G~γ_a curves of the marine silty clays are higher than those
λ~γ_a curves of the Pleistocene marine soils are lower than those
G~γ_a curves of the Pleistocene continental silt clays. However, the effect of geological age on the λ~γ_a curves is quite weak. Overall, geological age has less
effect on the λ~γ_a curves of the continental soils than
of the marine soils.

Figure 5 illustrates the effects of marine and continental
depositional, geological age has a clear e-
tect of geological age on the
G/G_{max}~γ_a and λ~γ_a curves due to the limited number of sampling sites,
the Pleistocene soils were not further classified into different
geological age categories: the Pleistocene versus the
Holocene (Figure 6). The results show that in general,
the geological age strongly affects the G/G_{max}~γ_a and λ~γ_a curves of the marine soils (silt clays and silt sands). The G/G_{max}~γ_a curves of the Pleistocene marine soils are higher than those of the Holocene marine soils while
G/G_{max}~γ_a curves of the Pleistocene marine soils are lower than those of the Holocene marine soils. For continental
depositional, geological age has a clear effect on the G/
G_{max}~γ_a curves of the continental silt clays. The G/G_{max}~γ_a curves of the Pleistocene continental silt clays are sig-
nificantly higher than those of the Holocene continental silt clays. However, the effect of geological age on the λ~γ_a curves is quite weak. Overall, geological age has less
effect on the λ~γ_a curves of the continental soils than
of the marine soils.

Figure 3: Typical results of resonant column test.

Figure 4: Variation relationship of the maximum dynamic shear modulus G_{max} with depth.
Figure 5: Comparison of $G/G_{\text{max}} \sim \gamma_a$ curve and $\lambda \sim \gamma_a$ fitting curves between marine deposit and continental deposit.

Figure 6: Influence of geological age on $G/G_{\text{max}} \sim \gamma_a$ curve and $\lambda \sim \gamma_a$ fitting curves of different deposits.
Table 3: Recommended parameter values for $G/G_{\text{max}} - \gamma_a$ and $\lambda - \gamma_a$ curves of Quaternary sedimentary soils in the offshore areas of the Yellow Sea.

| Lithology          | Geological age/deposit | Number of samples | $A$  | $B$  | $y_a (10^{-4})$ | $\lambda_{\text{min}}$ | $\lambda_0$ | $\beta$ |
|--------------------|------------------------|-------------------|------|------|-----------------|------------------------|-------------|--------|
| Silt clay          | Holocene               | 17                | 1.01 | 0.48 | 4.77            | 0.034                  | 0.132       | 1.477  |
|                    | Pleistocene            | 34                | 1.12 | 0.40 | 6.93            | 0.029                  | 0.136       | 1.363  |
| Silt sand          | Holocene               | 5                 | 1.15 | 0.39 | 2.22            | 0.007                  | 0.127       | 1.085  |
|                    | Pleistocene            | 15                | 1.17 | 0.39 | 3.01            | 0.013                  | 0.115       | 1.226  |
| Clay               | Continental depositional | 10              | 1.05 | 0.42 | 5.52            | 0.038                  | 0.161       | 1.732  |
|                    | Marine depositional    | 9                 | 1.09 | 0.41 | 7.32            | 0.034                  | 0.116       | 1.376  |

Table 4: Average values of $G/G_{\text{max}}$ and $\lambda$ at various shear strain levels for Quaternary sedimentary soils in the offshore areas of the Yellow Sea.

| Lithology          | Geological age/deposit | Parameters | $0.05$ | $0.1$ | $0.5$ | $1.0$ | $5.0$ | $10$ | $50$ | $100$ |
|--------------------|------------------------|------------|--------|------|------|------|------|-----|-----|------|
| Silt clay          | Holocene               | $G/G_{\text{max}}$ | 0.9883 | 0.9774 | 0.9004 | 0.8220 | 0.4933 | 0.3328 | 0.0958 | 0.0516 |
|                    |                        | $\lambda$ (%) | 3.39   | 3.42  | 3.81  | 4.40  | 8.19  | 10.61 | 14.71 | 15.54 |
|                    | Pleistocene            | $G/G_{\text{max}}$ | 0.9884 | 0.9772 | 0.9139 | 0.8545 | 0.6043 | 0.4640 | 0.1914 | 0.1199 |
|                    |                        | $\lambda$ (%) | 2.90   | 2.95  | 3.35  | 3.85  | 6.72  | 8.69  | 13.07 | 14.32 |
| Silt sand          | Holocene               | $G/G_{\text{max}}$ | 0.9685 | 0.9437 | 0.8078 | 0.7016 | 0.3875 | 0.2668 | 0.0929 | 0.0562 |
|                    |                        | $\lambda$ (%) | 1.00   | 1.26  | 2.83  | 4.13  | 8.18  | 9.79  | 12.15 | 12.65 |
|                    | Pleistocene            | $G/G_{\text{max}}$ | 0.9774 | 0.9587 | 0.8499 | 0.7581 | 0.4525 | 0.3210 | 0.1166 | 0.0711 |
|                    |                        | $\lambda$ (%) | 1.38   | 1.50  | 2.40  | 3.30  | 6.78  | 8.45  | 11.18 | 11.81 |
| Clay               | Continental depositional | $G/G_{\text{max}}$ | 0.9852 | 0.9730 | 0.8968 | 0.8256 | 0.5395 | 0.3926 | 0.1409 | 0.0835 |
|                    |                        | $\lambda$ (%) | 3.81   | 3.83  | 4.12  | 4.58  | 8.00  | 10.58 | 16.16 | 17.62 |
|                    | Marine depositional    | $G/G_{\text{max}}$ | 0.9883 | 0.9787 | 0.9181 | 0.8601 | 0.6092 | 0.4659 | 0.1875 | 0.1157 |
|                    |                        | $\lambda$ (%) | 3.45   | 3.48  | 3.80  | 4.20  | 6.62  | 8.33  | 12.17 | 13.25 |

As was previously discussed, the soils formed in the Quaternary marine sedimentary environment in the offshore areas of the Yellow Sea have significantly different dynamic shear modulus ratios and damping ratios than those formed in the Quaternary continental sedimentary environment. The effect of geological age on $G/G_{\text{max}}$ is similar to its effect on $\lambda$, while the effect on $G/G_{\text{max}}$ is slightly greater than that on $\lambda$. For ease of application in practical engineering, the fitting parameters of the $G/G_{\text{max}} - \gamma_a$ curves and the $\lambda - \gamma_a$ curves were obtained for each type of the classified samples (Table 3). For silty clay and silt, the newer the sedimentary age, the smaller the value of $A$ and the bigger the value of $B$. The average $G/G_{\text{max}}$ and $\lambda$ values at various shear strain levels calculated by the recommended parameters are presented in Table 4.

5. Conclusions

The sedimentary characteristics of the Quaternary soils formed during the transgression in the offshore areas of the Yellow Sea were investigated. The dynamic shear modulus ratios and the damping ratios of the soil samples were tested considering the effects of sedimentary environments, geological ages, and soil types. The main conclusions are as follows.

1. The $G_{\text{max}}$ of various marine soils increases with the depth and shows a typical linear relationship.

2. The effects of marine transgression on the $G/G_{\text{max}} - \gamma_a$ and $\lambda - \gamma_a$ curves of the Quaternary soils in the offshore areas of the Yellow Sea are significant. The effects are strong on the clays, moderate on the silty clays, and minor on the silts. The $G/G_{\text{max}} - \gamma_a$ and $\lambda - \gamma_a$ curves of the Pleistocene marine clays are higher and lower than those of the continental clays, respectively, which may be due to the higher strength of the clay crust formed during the marine transgression.

3. The effects of geological ages on the $G/G_{\text{max}} - \gamma_a$ and $\lambda - \gamma_a$ curves of the Quaternary soils in the offshore areas of the Yellow Sea have significant differences between soil type. The effects were strong on the marine silty clays, marine silts, and continental silty clays.
(4) Compared with the sedimentary environment, geological age generally had greater effect on the $G/G_{\text{max}} \sim \gamma_s$ and $\lambda \sim \gamma_s$ curves of the various types of Quaternary soils in the offshore areas of the Yellow Sea. The fitting parameters of the $G/G_{\text{max}} \sim \gamma_s$ and $\lambda \sim \gamma_s$ curves were obtained for each soil type under different sedimentary environments and geological ages. Moreover, the averaged curves for each type of soil were recommended for the application in practical engineering.

Data Availability

The data are generated from experiments and can be available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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