PLURIPOTENTIAL THEORY ON TEICHMÜLLER SPACE I
– PLURICOMPLEX GREEN FUNCTION –

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Abstract. This is the first paper in a series of investigations of the pluripotential theory on Teichmüller space. The main purpose of this paper is to give an alternative approach to the Krushkal formula of the pluricomplex Green function on Teichmüller space. We also show that Teichmüller space carries a natural stratified structure of real-analytic submanifolds defined from the structure of singularities of the initial differentials of the Teichmüller mappings from a given point. We will also give a description of the Levi form of the pluricomplex Green function using the Thurston symplectic form via the Dumas symplectic structure on the space of holomorphic quadratic differentials.

1. Introduction

This is the first paper in a series of investigations of the pluripotential theory on Teichmüller space. The main purpose of this paper is to give a characterization of the pluricomplex Green function on Teichmüller space. The characterization given here is first discussed by Krushkal in [28]. We prove the characterization from a different approach. In the second paper, we will establish the Poisson integral formula for pluriharmonic functions on Teichmüller space which are continuous on the Bers compactification. The characterization of the pluricomplex Green function given here plays a crucial role in the second paper. This result is announced in [34].

Let $T_{g,m}$ be the Teichmüller space of Riemann surfaces of analytically finite type $(g,m)$, and $d_T$ the Teichmüller distance on $T_{g,m}$. Teichmüller space $T_{g,m}$ admits a natural complex structure. Royden [39] proved that the Teichmüller distance coincides with the Kobayashi distance under the complex structure. Krushkal [27] showed that Teichmüller space is hyperconvex. By Bers’ theorem and Nehari-Kraus’ theorem, $T_{g,m}$ is biholomorphic to a bounded domain in the complex Euclidean space (cf. [19, Theorem 6.6]). Therefore, from Demailly’s theory [6], $T_{g,m}$ admits a unique pluricomplex Green function $g_{T_{g,m}}(x,y)$ (cf. [7,1]).

1.1. The Krushkal formula. The aim of this paper is to give an alternate proof of the Krushkal formula as follows.
Theorem 1 (Pluricomplex Green function on $T_{g,m}$). The pluricomplex Green function on $T_{g,m}$ satisfies

$$g_{T_{g,m}}(x,y) = \log \tanh d_T(x,y)$$

for $x, y \in T_{g,m}$.

From Klimek’s work [22], it suffices to show that the right-hand side of (1.1) is plurisubharmonic (cf. §7.1). To show this, Krushkal applied Poletskii’s characterization of the pluricomplex Green function (cf. [37]). Our strategy is a more direct method. Indeed, we calculate the Levi form of the log-tanh of the Teichmüller distance at generic points, and to check the non-negative definiteness (§7.6).

From the calculation, we deduce that the Levi-form of the pluricomplex Green function is described by the Thurston symplectic form on the space $M\mathcal{F}$ of measured foliations via the Dumas symplectic structure (cf. [9]) on the space of holomorphic quadratic differentials. This description induces a condition for deformations of Teichmüller mappings from a fixed basepoint to complex-analytically varying targets from the topological aspect in Teichmüller theory (cf. §7.7).

1.2. Stratification of Teichmüller space and Removable singularities. Dumas [9] gave a complex-analytic stratification in the space $Q_{x_0}$ of (non-zero) holomorphic quadratic differentials on $x_0 \in T_{g,m}$ in terms of the structure of singularities. (cf. §2.2). Sending the stratification on $Q_{x_0}$ by the Teichmüller homeomorphism (§2.2.2), we obtain a topological stratification on $T_{g,m} - \{x_0\}$. The top stratum $T_\infty$ consists of $x \in T_{g,m} - \{x_0\}$ such that the initial differential of the Teichmüller mapping from $x_0$ to $x$ is generic. We will show that the induced stratification on $T_{g,m} - \{x_0\}$ is a real-analytic stratification in the sense that each stratum is a real-analytic submanifold (cf. Theorem 5). Applying the stratification, we shall show the following, which is crucial in our proof of Theorem 1 (cf. §6.3).

Theorem 2 (Non-generic strata are removable). A function of class $C^1$ on $T_{g,m} - \{x_0\}$ is plurisubharmonic on $T_{g,m}$ if it is plurisubharmonic on the top stratum $T_\infty$ and bounded above around $x_0$.

1.3. About the paper. This paper is organized as follows. From §2 to §4 we recall the basic notion and properties in Teichmüller theory. In §5 we discuss the deformation of singular Euclidean structures associated to the Teichmüller deformations from a fixed point $x_0 \in T_{g,m}$. In §6 we will give the stratification on $T_{g,m} - \{x_0\}$. We show Theorem 1 and discuss the topological description of the Levi form in §7.

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2. TEICHMÜLLER THEORY

Let $\Sigma_{g,m}$ be a closed orientable surface of genus $g$ with $m$-marked points with $2g - 2 + m > 0$ (possibly $m = 0$). In this section, we recall basics in Teichmüller theory. For reference, see [7], [12], [18], [19], and [35] for instance.
2.1. Teichmüller space. Teichmüller space $\mathcal{T}_{g,m}$ is the set of equivalence classes of marked Riemann surfaces of type $(g,m)$. A marked Riemann surface $(M,f)$ of type $(g,m)$ is a pair of a Riemann surface $M$ of analytically finite type $(g,m)$ and an orientation preserving homeomorphism $f: \Sigma_{g,m} \to M$. Two marked Riemann surfaces $(M_1,f_1)$ and $(M_2,f_2)$ of type $(g,m)$ are (Teichmüller) equivalent if there is a conformal mapping $h: M_1 \to M_2$ such that $h \circ f_1$ is homotopic to $f_2$.

The Teichmüller distance $d_T$ is a complete distance on $\mathcal{T}_{g,m}$ defined by
$$d_T(x_1,x_2) = \frac{1}{2} \log \inf_h K(h)$$
for $x_i = (M_i,f_i)$ ($i = 1, 2$), where the infimum runs over all quasiconformal mapping $h: M_1 \to M_2$ homotopic to $f_2 \circ f_1^{-1}$, and $K(h)$ is the maximal dilatation of a quasiconformal mapping $h$.

2.2. Quadratic differentials and Infinitesimal complex structure on $\mathcal{T}_{g,m}$. For $x = (M,f) \in \mathcal{T}_{g,m}$, we denote by $\mathcal{Q}_x$ be the complex Banach space of holomorphic quadratic differentials $q = q(z)dz^2$ on $M$ with $L^1$-norm
$$\|q\| = \int_M |q(z)| \frac{\sqrt{-1}}{2} dz \wedge d\overline{z} < \infty.$$ 
From the Riemann-Roch theorem, the space $\mathcal{Q}_x$ is isomorphic to $\mathbb{C}^{3g-3+m}$. Let
$$\Pi: \mathcal{Q}_{g,m} = \bigcup_{x \in \mathcal{T}_{g,m}} \mathcal{Q}_x \to \mathcal{T}_{g,m}$$
be the complex vector bundle of quadratic differentials over $\mathcal{T}_{g,m}$. A differential $q \in \mathcal{Q}_{g,m}$ is said to be generic if all zeros are simple and all marked points of the underlying surface are simple poles of $q$. Generic differentials are open and dense subset in $\mathcal{Q}_{g,m}$ and in each fiber $\mathcal{Q}_x$ for $x \in \mathcal{T}_{g,m}$.

2.2.1. Infinitesimal complex structure. The Teichmüller space $\mathcal{T}_{g,m}$ is a complex manifold of dimension $3g-3+m$. The infinitesimal complex structure is described as follows: Let $x = (M,f) \in \mathcal{T}_{g,m}$. Let $L^\infty(M)$ be the Banach space of measurable $(-1,1)$-forms $\mu = \mu(z)d\overline{z}/dz$ on $M$ with
$$\|\mu\|_\infty = \text{ess.sup}_{p \in M} |\mu(p)| < \infty.$$ 
The holomorphic tangent space $T_x \mathcal{T}_{g,m}$ at $x$ of $\mathcal{T}_{g,m}$ is described as the quotient space
$$L^\infty(M)/\{\mu \in L^\infty(M)\mid \langle \mu, \varphi \rangle = 0, \forall \varphi \in \mathcal{Q}_x\},$$
where
$$\langle \mu, \varphi \rangle = \int_M \mu(z)\varphi(z) \frac{\sqrt{-1}}{2} dz \wedge d\overline{z}.$$ 
For $v = [\mu] \in T_x \mathcal{T}_{g,m}$ and $\varphi \in \mathcal{Q}_x$, the canonical pairing between $T_x \mathcal{T}_{g,m}$ and $\mathcal{Q}_x$ is defined by
$$\langle v, \varphi \rangle = \langle \mu, \varphi \rangle$$
and, it induces an identification between $\mathcal{Q}_x$ and the holomorphic cotangent space $T^*_x \mathcal{T}_{g,m}$.
2.2.2. The Teichmüller homeomorphism. Let $UQ_x$ be the unit ball in $Q_x$. For $q \in UQ_x$, we define a quasiconformal mapping $f^q$ on $M$ from the Beltrami differential $\|q\| (\overline{f/|q|}) \in L^\infty(M)$. Then, $T_{g,m}$ is homeomorphic to $UQ_x$ with
\begin{equation}
\Xi = \Xi_x : UQ_x \ni q \mapsto (f^q(M), f^q \circ f) \in T_{g,m}.
\end{equation}
We call the homeomorphism (2.1) the Teichmüller homeomorphism. The Teichmüller homeomorphism gives a useful representation of the Teichmüller distance as
\begin{equation}
d_T(x, \Xi_x(q)) = \frac{1}{2} \log \frac{1 + \|q\|}{1 - \|q\|} = \tanh^{-1}(\|q\|)
\end{equation}
for $q \in UQ_x$.

2.3. Measured foliations. Let $S$ be the set of homotopy classes of non-trivial and non-peripheral simple closed curves on $\Sigma_{g,m}$. Let $i(\alpha, \beta)$ denote the geometric intersection number for simple closed curves $\alpha, \beta \in S$. Let $WS = \{t\alpha \mid t \geq 0, \alpha \in S\}$ be the set of weighted simple closed curves. The set $S$ is canonically identified with a subset of $WS$ as weight 1 curves.

We consider an embedding $WS \ni t\alpha \mapsto [S \ni \beta \mapsto ti(\alpha, \beta)] \in \mathbb{R}^S_{\geq 0}$. We topologize the function space $\mathbb{R}^S_{\geq 0}$ with the topology of pointwise convergence. The closure $MF$ of the image of the embedding is called the space of measured foliations on $\Sigma_{g,m}$. The space $MF$ is homeomorphic to $\mathbb{R}^{6g-6+2m}$, and contains the weighted simple closed curves $WS$ as a dense subset. The intersection number on $WS$ is defined by $i(t\alpha, s\beta) = ts i(\alpha, \beta)$ for $t\alpha, s\beta \in WS$. The intersection number extends continuously as a non-negative function $i(\cdot, \cdot)$ on $MF \times MF$ with $i(F, F) = 0$ and $F(\alpha) = i(F, \alpha)$ for $F \in MF \subset \mathbb{R}^S_{\geq 0}$ and $\alpha \in S$.

2.4. Hubbard-Masur differentials and Extremal length. Let $x = (M, f) \in T_{g,m}$. For $q \in Q_x$, the vertical foliation $v(q)$ of $q$ is a measured foliation defined by
\begin{equation}
i(v(q), \alpha) = \inf_{\alpha' \in f(\alpha)} \int_{\alpha'} |\text{Re}(\sqrt{q})|
\end{equation}
for $\alpha \in S$. Hubbard and Masur observed that the correspondence, which we call the Hubbard-Masur homeomorphism,
\begin{equation}
V_x : Q_x \ni q \mapsto v(q) \in MF
\end{equation}
is a homeomorphism (cf. [17] and Remark [9]). For $F \in MF$, the Hubbard-Masur differential $qF_{,x}$ for $F$ at $x$ is defined to satisfy $v(qF_{,x}) = F$. By definition, $qF_{,x} = t^2 qF_{,x}$ for $F \in MF$ and $t \geq 0$.

For $F \in MF$, the extremal length of $F$ at $x$ is defined by
\begin{equation}
\text{Ext}_x(F) = \|qF_{,x}\|.
\end{equation}
Kerckhoff [21] observed that the Teichmüller distance is expressed as
\begin{equation}
d_T(x, y) = \frac{1}{2} \log \sup_{\alpha \in S} \frac{\text{Ext}_x(\alpha)}{\text{Ext}_y(\alpha)}
\end{equation}
for $x, y \in T_{g,m}$. This expression is called the Kerckhoff formula of the Teichmüller distance.
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Figure 1. The covering space $\pi_{q_0} : \tilde{M}_{q_0} \to M_0$; Symbols $\circ$, $\Box$ and $\times$ in the figure mean non-orientable singularities, orientable singularities, and marked points, respectively. Each singularity may coincide with a marked point (denoted by $\otimes$ for non-orientable singularities and by $\varnothing$ otherwise). Points $\otimes$ may or may not be poles of $q_0$. In our notation, $\Sigma(q_0) = \{\circ, \otimes, \Box, \times\}$, $\Sigma_s(q_0) = \{\otimes, \Box\}$, $\Sigma_m(q_0) = \{\times\}$, $\Sigma_{sm}(q_0) = \{\circ, \otimes, \Box, \times, \varnothing\}$, $\Sigma_{ub}(q_0) = \{\times, \varnothing\}$, $\Sigma_o(q_0) = \{\circ, \otimes\}$, and $\Sigma_e(q_0) = \{\Box, \varnothing\}$.

3. Double covering spaces associated to quadratic differentials

3.1. Branched covering spaces. Let $x_0 = (M_0, f_0) \in T_{g,m}$. Let $\Sigma_m = \Sigma_m(x_0)$ be the marked points of $M_0$. Let $q_0 \in Q_{x_0} \subset Q_{g,m}$. Let $\Sigma_s(q_0)$ be the set of singularities of $q_0$. In accordance with [32], a singular point of $q_0$ is called orientable if it is of even order, and non-orientable otherwise. Any orientable singular point is a zero of $q_0$. Let $\Sigma_o = \Sigma_o(q_0)$ (resp. $\Sigma_e = \Sigma_e(q_0)$) be the set of non-orientable (resp. orientable) zeros of $q_0$ (“o” and “e” stand for “odd” and “even”). The number of non-orientable singularities is always even. By definition, $\Sigma_s(q_0) = \Sigma_o(q_0) \cup \Sigma_e(q_0)$. We define

$$
\begin{align*}
\Sigma(q_0) &= \Sigma_e(q_0) \cup \Sigma_o(q_0) \cup \Sigma_m(x_0), \\
\Sigma_{sm}(q_0) &= \Sigma_s(q_0) \cap \Sigma_m(x_0), \\
\Sigma_{s\backslash m}(q_0) &= \Sigma_s(q_0) \setminus \Sigma_m(x_0), \\
\Sigma_{m\backslash s}(q_0) &= \Sigma_m(x_0) \setminus \Sigma_s(q_0), \\
\Sigma_{ub}(q_0) &= \Sigma_e(q_0) \cup \Sigma_{m\backslash s}(q_0).
\end{align*}
$$

We call a marked point in $\Sigma_{m\backslash s}(q_0)$ free. The set $\Sigma(q_0)$ is the totality of marked points caused by $q_0$, and it is represented as the disjoint unions

$$\Sigma(q_0) = \Sigma_{ub}(q_0) \cup \Sigma_o(q_0).$$

Consider the double branched covering space $\pi_{q_0} : \tilde{M}_{q_0} \to M_0$ of the square root $\sqrt{q_0}$ (cf. Figure 1). For $p \in \Sigma(q_0)$, the preimage $\pi_{q_0}^{-1}(p)$ consists of two points if and only if $p \in \Sigma_{ub}(q_0)$ (“ub” stands for “unbranched”). The projection $\pi_{q_0}$ is
double-branched over points in \( \tilde{\Sigma}_\omega(q_0) \). The surface \( \tilde{M}_{q_0} \) is a closed surface of genus \( g \) and genus \( \eta \) for all \( q_0 \) (cf. \([1, \S 3.3]\)). In particular, the surface \( \tilde{M}_{q_0} \) is a closed Riemann surface of genus \( 4g - 3 + m \) when \( q_0 \) is generic. The square root \( \sqrt{q_0} \) on \( M_0 \) is lifted as the Abelian differential \( \omega_{q_0} \) on \( \tilde{M}_{q_0} \). The covering transformation \( i_{q_0} \) of the covering is a conformal involution on \( \tilde{M}_{q_0} \) which satisfies \( \pi_{q_0} \circ i_{q_0} = \pi_{q_0} \) and \( i_{q_0}^* \omega_{q_0} = -\omega_{q_0} \). For each set \( \Sigma_{q_0}(q_0) \) defined above, we denote by \( \bar{\Sigma} \) the preimage of \( \Sigma(q_0) \). When \( q_0 \) is square in the sense that \( q_0 = \omega^2 \) for some Abelian differential \( \omega \) on \( M_0 \), \( \tilde{M}_{q_0} \) consists of two copies of \( M_0 \).

We consider the pair \( (\tilde{M}_{q_0}, \Sigma_{ab}(q_0)) \) as a Riemann surface with marked points.

**Convention** Let \( V \) be a vector space \( V \) with an involution. We denote by \( V^\pm \) the eigenspace in \( V \) of the eigenvalue \( \pm 1 \) of the action of the involution. \( \Box \)

We also remark the following elementary fact: For vector spaces \( V \) with an involution \( (i = 1, 2, 3) \), an exact sequence \( 0 \to V_1 \to V_2 \to V_3 \to 0 \) commuting the involutions induces an exact sequence \( 0 \to V_1^i \to V_2^i \to V_3^i \to 0 \).

### 3.2. A subspace in quadratic differentials

For \( q_0 \in Q_{x_0} \) and \( x_0 = (M_0, f_0) \), we define

\[
Q_{x_0}^T(q_0) = \left\{ \psi \in Q_{x_0} \mid (\psi) \geq \prod_{p \in \Sigma_{\eta_m}(q_0)} p^{\eta(p)} - 1 \prod_{p \in \Sigma_{\eta_m}(q_0)} p^{\eta(p)} \right\}.
\]

where \( \eta(p) \) is the order of \( q_0 \) at \( p \in M_0 \), and \( (\psi) \) is the divisor of \( \psi \). The symbol “\( T \)” stands for “tangent”. When \( M_0 \) has no marked point (i.e. \( m = 0 \)), \( \psi \in Q_{x_0}^T(q_0) \) is equivalent to the condition that \( \psi/q_0 \) has at most simple poles on \( M_0 \) (cf. \([9, \text{Lemma 5.2}]\). See also Proposition \([6, 1]\) below). Notice that \( Q_{x_0}^T(q_0) = Q_{x_0} \) if \( q_0 \) is generic.

### 3.3. The \( q \)-realizations of tangent vectors

Let \( x_0 = (M_0, f_0) \in T_{g,m} \) and \( q_0 \in Q_{x_0} - \{0\} \) be a generic differential. For \( v \in T_{x_0}T_{g,m} \), a holomorphic quadratic differential \( \eta_{v} \in Q_{x_0} \) said to be the \( q_0 \)-realization of \( v \) if it satisfies

\[
\langle v, \psi \rangle_{x_0} = \int_{M_0} \frac{\bar{\eta_{v}}}{|q_0|} \psi
\]

for all \( \psi \in Q_{x_0} \) where \( x_0 = (M_0, f_0) \in T_{g,m} \) (cf. \([33]\)). Notice that \( \eta_v \) in \((3.1)\) does exist because

\[
(\psi_1, \psi_2) \mapsto \int_{M_0} \frac{\bar{\psi_1} \psi_2}{|q_0|}
\]

is a non-degenerate Hermitian inner product on \( Q_{x_0} \) (cf. \([9, \S 5]\)). The correspondence

\[
T_{x_0}T_{g,m} \ni v \mapsto \eta_{v} \in Q_{x_0}
\]
is an anti-complex linear isomorphism. The Hermitian form \( (3.2) \) is calculated as

\[
\int_{M_0} \psi_1 \psi_2 = \frac{-1}{4} \int_{M_0} \frac{\pi_{g_0}^*(\psi_1) \wedge \pi_{g_0}^*(\psi_2)}{\omega_{q_0}}
\]

\[
= \frac{1}{2} \int_{M_{q_0}} \text{Re} \left( \frac{\pi_{g_0}^*(\psi_1)}{\omega_{q_0}} \right) \wedge \text{Im} \left( \frac{\pi_{g_0}^*(\psi_2)}{\omega_{q_0}} \right)
\]

\[
+ \frac{1}{2} \int_{\tilde{M}_{q_0}} \text{Re} \left( \frac{\pi_{g_0}^*(\psi_1)}{\omega_{q_0}} \right) \wedge \text{Re} \left( \frac{\pi_{g_0}^*(\psi_2)}{\omega_{q_0}} \right)
\]

for \( \psi_1, \psi_2 \in Q_{x_0} \).

4. Stratifications on \( Q_{g,m} \)

4.1. Stratification. Following Dumas [9], we recall the definition of stratifications on manifolds. Let \( Z \) be a manifold. A stratification of \( Z \) is a locally finite collection of locally closed submanifolds \( \{ Z_i \}_{i \in I} \) of \( Z \), the strata, indexed by a set \( I \) such that

1. \( Z = \bigcup_{j \in I} Z_j \)
2. \( Z_j \cap Z_k \neq \emptyset \) if and only if \( Z_j \subset \overline{Z_k} \).

From the second condition, \( Z_j \cap Z_k \neq \emptyset \) if and only if \( Z_j = Z_k \) because each \( Z_i \) is locally closed. A stratification of a complex manifold \( Z \) a complex-analytic stratification if the closure \( \overline{Z_j} \) and the boundary \( \overline{Z_j} \setminus Z_j \) of each stratum \( Z_j \) are complex-analytic sets.

4.2. Strata in \( Q_{g,m} \). Our strata and symbol are slightly different from that treated by Masur-Smithie [32] and Veech [44]. We consider here the deformation of quadratic differentials with marked points for our purpose (see also [44, §4.3] below). If any marked point of given quadratic differential is a singular point, our strata are coincides with their strata (cf. [44, §1]).

A symbol of \( q \in Q_{g,m} \setminus \{ \emptyset \} \) is a quadruple \( \pi = (m, n(-1), n(\cdot), \varepsilon) \) where \( m \) is the number of free marked points, \( n(-1) \) is the number of poles, \( n(l) \) is the number of zeros of order \( l \geq 1 \), and \( \varepsilon = \pm 1 \) according to whether \( q \) is square \( (\varepsilon = 1) \) or not \( (\varepsilon = -1) \). We set \( n(0) = 0 \) for simplicity. Notice that \( \sum_{l \geq -1} l \cdot n(l) = 4g - 4 \).

Let \( Q(\pi) = Q_{g,m}(\pi) \subset Q_{g,m} \) be the set of holomorphic quadratic differentials in \( Q_{g,m} \) whose symbol is \( \pi \). As we discuss in Proposition 4.1 below, each component of \( Q(\pi) \) is a complex manifold of dimension

\[
dim \mathcal{Q}(\pi) = 2g + \frac{\varepsilon - 3}{2} + m + \sum_{l \geq -1} n(l).
\]

Let \( \pi(q) = (m_q, n_q(-1), n_q(\cdot), \varepsilon_q) \) be the symbol of \( q \in Q_{g,m} \). If \( \Sigma_s(q) = \emptyset \), we have \( q = 1 \) and \( q \) is square. We set \( \pi(q) = (m, 0, \{ 0, \cdots, 1 \} ) \) in this case.

Since \( m_q + \sum_{l \geq -1} n_q(l) = \# \Sigma(q) = \# \Sigma_0(q) + \# \Sigma_{ub}(q) \) for \( q \in Q_{g,m} \), from (4.1), we can check the following.

\[
\dim \mathcal{Q}(\pi(q)) = \dim \text{Hom}(H_1(\hat{M}_g, \tilde{\Sigma}_{ub}(q), \mathbb{R}), \mathbb{C}).
\]

4.3. Remark on the stratification on \( Q_{g,m} \). Our stratification of \( Q_{g,m} \) is slightly different from Masur-Smithie-Veech’s one in the following sense: We have mainly two differences from their stratification:
(1) If a free marked point and a singular point collide in a moving of quadratic differentials, we recognize the quadratic differentials to be degenerating into the other stratum. Two free marked points cannot collide because we consider the deformation on $T_{g,m}$; and

(2) if a singular point of a quadratic differential in a stratum lies at a marked point, the singular point stays on the marked point in deforming on the stratum for the quadratic differential.

All of these phenomena can be handled by standard arguments with complex analysis (for instance, [32] and [43]).

4.4. Masur-Smillie-Veech charts of the strata in $Q_{g,m}$. For $q_0 \in Q(\pi(q_0))$, the union $\bigcup_q \tilde{M}_q$ is regarded as a trivial bundle over a small contractible neighborhood of $q_0$ whose fiber is a (possibly disconnected) surface with marked points. For each $q \in Q(\pi(q_0))$ which is sufficiently close to $q_0$, the surface $\tilde{M}_q$ admits a marking inherited from the product structure of the bundle. Hence, we can identify $H_1(\tilde{M}_q, \Sigma_{ub}(q_0), \mathbb{R})$ with $H_1(\tilde{M}_{q_0}, \Sigma_{ub}(q_0), \mathbb{R})$ for $q \in Q(\pi(q_0))$ near $q_0$ in the canonical manner.

The following is well-known (e.g. [32], [31], [43] and [44]).

Proposition 4.1 (Local chart). There is a neighborhood $V_0$ of $q_0$ in $Q(\pi(q_0))$ such that the mapping

$$\Phi_0 : V_0 \ni q \mapsto \left[C \mapsto \int_C \omega_q\right] \in \text{Hom}(H_1(\tilde{M}_{q_0}, \Sigma_{ub}(q_0), \mathbb{R}), \mathbb{C})$$

is a holomorphic local chart around $q_0$.

5. Deformations of quadratic differentials

Henceforth, we set $\text{Hom}(q_0) = \text{Hom}(H_1(\tilde{M}_{q_0}, \Sigma_{ub}(q_0), \mathbb{R}), \mathbb{C})$ for the simplicity. From Proposition 4.1, $T_{q_0} Q(\pi(q_0))$ is isomorphic to $\text{Hom}(q_0)$ as $\mathbb{C}$-vector spaces.

In this section, we consider a $\Delta$-complex structure on $\tilde{M}_{q_0}$ for given $q_0 \in Q_{g,m}$, and describe the infinitesimal deformations along elements in $T_{q_0} Q(\pi(q_0)) \cong \text{Hom}(q_0)$ by piecewise affine deformations.

5.1. $\Delta$-complex structure. A $\Delta$-complex structure on a space $X$ is a collection of a singular simplex $\sigma_\alpha : \Delta^n \to X$ ($\Delta^n$ is the standard $n$-simplex), with $n = n(\alpha)$ such that

(1) the restriction $\sigma_\alpha$ to the interior of $\Delta^n$ is injective, and each point of $X$ is in the image of exactly one such restriction;

(2) each restriction of $\sigma_\alpha$ to a face of $\Delta^n$ is one of the maps $\sigma_\beta : \Delta^{n-1} \to X$.

Here, we are identifying the face of $\Delta^n$ with $\Delta^{n-1}$ by the canonical linear homeomorphism between them that preserves the ordering of the vertices; and

(3) a set $A \subset X$ is open if and only if $\sigma_\alpha^{-1}(A)$ is open in $\Delta^n$ for each $\sigma_\alpha$ (cf. [16], §2.1). A $\Delta$-complex structure on a surface gives a kind of triangulations. The (relative) (co)homology group defined by a $\Delta$-complex structure on a space $X$ coincides with the (relative) (co)homology group of $X$ (cf. [16]).
5.2. **Singular Euclidean structure on** \( \tilde{M}_{q_0} \). Let \( x_0 = (M_0, f_0) \in T_{g,n} \) and \( q_0 \in Q_{x_0} \). Consider a \( \Delta \)-complex structure \( \Delta \) on \( M_0 \) such that the 0-skeleton \( \Delta^{(0)} \) contains \( \Sigma(q_0) \), each 1-simplex is a straight segment with respect to the \( |q_0| \)-metric, and each 2-simplex is a non-degenerate triangle. Such a \( \Delta \)-complex exists. For instance, we can take it as a refinement (subdivision) of the Delaunay triangulation with respect to the singularities of \( q_0 \) (cf. [122 §4]). Let \( \tilde{\Delta} \) be the lift of \( \Delta \). \( \tilde{\Delta} \) is a \( \Delta \)-complex structure on \( \tilde{M}_{q_0} \). The covering transformation \( i_{q_0} \) acts on the 1-chain group \( C_1(\tilde{\Delta}, \Sigma_{ub}(q_0), \mathbb{R}) \).

We define \( \tilde{u}[q_0] \in \text{Hom}(C_1(\tilde{\Delta}, \Sigma_{ub}(q_0))^{-}, \mathbb{C}) \) by

\[
\tilde{u}[q_0](e) = \int_e \omega_{q_0}
\]

for \( e \in C_1(\tilde{\Delta}, \Sigma_{ub}(q_0))^{-} \). The restriction of \( \tilde{u}[q_0] \) to the cycles \( Z_1(\tilde{\Delta}, \Sigma_{ub}(q_0), \mathbb{R})^{-} \) descends to a homomorphism \( u[q_0] \in \text{Hom}(q_0) \) such that \( \Phi_0(q_0) = u[q_0] \) (cf. Proposition 4.1).

5.3. **Piecewise affine deformations.** Let \( \sigma \) be a 2-simplex in \( \Delta \). Let \( \partial \sigma = e_1 + e_2 + e_3 \) as 1-chains. The developing mapping \( \sigma \ni p \mapsto z(p) = \int^p \omega_{q_0} \) maps \( \sigma \) to a Euclidean triangle \( \sigma' \) in the complex plane \( \mathbb{C} \) with (oriented) edges \( \tilde{u}[q_0](e_i) \). Notice that \( dz = \omega_{q_0} \) on \( \sigma' \) (cf. Figure 2).

For \( v \in \text{Hom}(q_0) \cong T_{g,n} \mathbb{Q}(\pi(q_0)) \), the infinitesimal deformation along \( v \) of the singular Euclidean structure associated to \( q_0 \) is described by an assortment of the affine deformation of the triangle \( \sigma \) along the lift \( \tilde{v} \in \text{Hom}(C_1(\tilde{\Delta}, \Sigma_{ub}(q_0), \mathbb{R})^{-}, \mathbb{C}) \) of \( v \). Here, we define the lift \( \tilde{v} \) as follows: We first take the pullback of \( v \) on \( Z_1(\tilde{\Delta}, \Sigma_{ub}(q_0), \mathbb{R})^{-} \) by precomposing the projection from \( Z_1(\tilde{\Delta}, \Sigma_{ub}(q_0), \mathbb{R})^{-} \) to \( H_1(\tilde{M}_{q_0}, \Sigma_{ub}(q_0), \mathbb{R})^{-} \), and set \( \tilde{v} \equiv 0 \) on a complementary space of \( Z_1(\tilde{\Delta}, \Sigma_{ub}(q_0), \mathbb{R})^{-} \) in \( C_1(\tilde{\Delta}, \Sigma_{ub}(q_0), \mathbb{R})^{-} \).

To be more precise, fix a norm on \( \text{Hom}(C_1(\tilde{\Delta}, \Sigma_{ub}(q_0), \mathbb{R})^{-}, \mathbb{C}) \). Since each 2-simplex of \( \Delta \) is a non-degenerate triangle, vectors \( \{(\tilde{u}[q_0] + \tilde{v})(e_i)\}_{i=1}^3 \) also span a non-degenerate triangle when \( \tilde{v} \) is sufficiently short. Collecting such new triangles defined from all 2-simplices of \( \tilde{\Delta} \), and gluing them according to the combinatorial structure \( \tilde{\Delta} \), we get a new singular Euclidean surface \( \tilde{M}_{q_0}[v] \) which is homeomorphic to \( \tilde{M}_{q_0} \), by a piecewise affine mapping \( \tilde{F}_v : \tilde{M}_{q_0} \to \tilde{M}_{q_0}[v] \) defined by assembling the affine deformations on the 2-simplices of \( \tilde{\Delta} \). Since \( i_{q_0}^*(\tilde{v}) = -\tilde{v} \), \( \tilde{M}_{q_0}[v] \) admits an involution \( i_{q_0}[v] \) satisfies \( i_{q_0}[v] \circ \tilde{F}_v = \tilde{F}_v \circ i_{q_0} \), and the piecewise affine mapping \( \tilde{F}_v \) descends to a quasiconformal mapping (a piecewise affine mapping) \( F_v \) on \( M_0 \) to a Riemann surface \( M_0[v] \). The surface \( \tilde{M}_{q_0}[v] \) admits a \( \Delta \)-complex structure \( \tilde{\Delta}[v] \).
inherited form $\Delta$ on $\tilde{M}_q$, which is equivariant under the action of the involution $i_{q_0}[v]$. The $\Delta$-complex structure $\Delta[v]$ descends to a $\Delta$-complex structure $\Delta[v]$ on $M_0[v]$.

Denote by $w$ the flat coordinate for $\tilde{M}_q$ (defined on each 2-simplex of $\Delta[v]$). The holomorphic 1-form $dw$ on each 2-simplex for $\tilde{M}_q$ defines a holomorphic 1-form $\omega_q[v]$ on $M_0[v]$. The square $\omega_q[v]^2$ descends to a holomorphic quadratic differential $q[q_0, v]$ on $M_0[v]$.

Let $x_v = (M_0[v], F_v \circ f_0) \in T_{g,m}$. Since $\tilde{F}_v$ sends the vertices of $\Delta$ to the vertices of $\Delta[v]$, we can see that $q[q_0, v] \in Q(\pi(q_0)) \cap Q_xv$ when $\bar{v}$ is sufficiently short, $q[q_0, 0] = q_0$ and

$$u[q_0, v](C) = \int_{(\tilde{F}_v)_{(C)}} \omega_{q_0}[v] = (u[q_0] + v)(C)$$

for all $C \in H_1(\tilde{M}_{q_0}, \tilde{\Sigma}_{ub}(q_0), \mathbb{R})^{-}$. Summarizing the above argument, we get a commuting diagram

$$\begin{array}{ccc}
\tilde{M}_q & \xrightarrow{\tilde{F}_v} & \tilde{M}_q[q_0, v] \\
\downarrow && \downarrow \\
M_0 & \xrightarrow{F_v} & M_0[v]
\end{array}$$

when the lift $\bar{v} \in \text{Hom}(C_1(\Delta, \tilde{\Sigma}_{ub}(q_0), \mathbb{R})^{-}, \mathbb{C})$ of $v \in \text{Hom}(q_0) \cong T_{q_0}Q(\pi(q_0))$ is sufficiently short, where the vertical directions are double-branched coverings with covering involutions $i_{q_0}$ and $i_{q_0}[v]$.

5.4. Teichmüller deformations. Let $x_0 = (M_0, f_0) \in T_{g,m}$ and $q_0 \in Q_{x_0}$. For $t \geq 0$, let $h_t: M_0 \rightarrow M_t$ be the Teichmüller mapping associated to the Betrami differential $\text{tanh}(t)\pi/|q_0|$ (cf. [2, 2.2]). Let $x_{t,q_0} = (M_t, h_t \circ f_0) \in T_{g,m}$ and Let $Q[t, q_0] \in Q_{x_{t,q_0}}$ be the terminal differential (e.g. [19]). For our purpose, we assume that the Teichmüller mapping $h_t$ is represented as an affine mapping associated to the matrix $\begin{pmatrix} 1 & 0 \\ 0 & e^{-2t} \end{pmatrix}$ in terms of the natural coordinates (distinguished parameters) of the initial and terminal differentials (cf. [42] Chapter II). In particular, $\|Q[t, q_0]\| = e^{-2t}\|q_0\|$ and $v(Q[t, q_0]) = v(q_0)$ from our assumption (cf. [17] Lemma 4.3) and (4.2) below. It is known that $Q[t, q_0] \in Q(\pi(q_0))$ for $t \geq 0$ (e.g. [24]).

The Teichmüller mapping $h_t$ lifts as a quasiconformal mapping $h_t: \tilde{M}_q \rightarrow \tilde{M}_{q_0}$ which is equivariant under the action of the involutions. The lift gives the identification $H_1(\tilde{M}_{Q[t, q_0]}, \tilde{\Sigma}_{ub}(Q[t, q_0]), \mathbb{R})^{-} \cong H_1(\tilde{M}_{q_0}, \tilde{\Sigma}_{ub}(q_0), \mathbb{R})^{-}$. By the analytic continuation along a continuous path $t \mapsto Q[t, q_0] \in Q(\pi(q_0))$ from initial point $q_0$, the chart given in Proposition 4.1 extends a neighborhood of the path. The image of $Q[t, q_0]$ by the chart satisfies

$$u[Q[t, q_0]](C) = \Re(u[q_0](C)) + \sqrt{1-e^{-2t}}\Im(u[q_0](C))$$

$$= \frac{1 + e^{-2t}}{2}u[q_0](C) + \frac{1 - e^{-2t}}{2}u[q_0](C)$$

for $C \in H_1(\tilde{M}_{q_0}, \tilde{\Sigma}_{ub}(q_0), \mathbb{R})^{-}$. 
5.5. Piecewise affine deformations around Teichmüller geodesics. Let $v \in \text{Hom}(\gamma_0) \cong T_{\gamma_0} Q(\pi(\gamma_0))$ and $t > 0$. When the lift $\tilde{v}$ is sufficiently short as (5.3) we defined $x_t \in T_{\gamma_0}$ and $q(\gamma_0, v) \in Q_{x_t}$ associated to $v$ (cf. §5.3). Consider the Teichmüller deformation on $x_t$ associated to $q(\gamma_0, v)$ and $t$. From the discussion in §5.4 the chart in Proposition 4.1 is defined around the terminal differential $Q[t, q(\gamma_0, v)]$ when the lift of $v$ is sufficiently short.

From (5.4) and (5.2), $Q[t, q(\gamma_0, 0)] = Q[t, q_0]$, $Q[0, q(\gamma_0, v)] = q(\gamma_0, v)$ and

\[(5.3) \quad u(Q[t, q(\gamma_0, v)])(C) = \text{Re} \left( (u(\gamma_0 + v))(C) \right) + \sqrt{-1} e^{-2t} \text{Im} \left( u(\gamma_0 + v) \right)(C)\]

for $t \geq 0$ and $C \in H_1(\tilde{M}_{\gamma_0}, \hat{\Sigma}_{\gamma_0}(\gamma_0), \mathbb{R})^-$ when the lift $\tilde{v}$ of $v$ in $\text{Hom}(\gamma_0)$ is sufficiently short.

5.6. The hypercohomology group. Following Hubbard-Masur [17], we recall the description of the holomorphic tangent space $T_q Q_{g,m}$ at $q \in Q_{g,m}$ as the first hypercohomology group $\mathbb{H}^1(L^*)$ a complex of sheaves (cf. [14] or [13]). We will need the Kodaira-Spencer identification of the tangent space of Teichmüller space with the first cohomology group of the sheaf of holomorphic vector fields (for instance, see [25]. See also [19] and [20]).

Let $X$ and $q$ be a holomorphic vector field and a holomorphic quadratic differential on an open set of a Riemann surface $M$. Denote by $L_X q$ the Lie derivative of $q$ along $X$. Let $\Theta_M$ and $\Omega_M^2$ be the sheaves of germs of holomorphic vector fields with zeroes at marked points and meromorphic quadratic differentials on $M$ with (at most) first order poles at marked points, respectively.

Let $\gamma_0 \in Q_{g,m}$ and $x_0 = (M_0, f_0) \in T_{\gamma_0}$ with $\gamma_0 \in Q_{x_0}$ ($\gamma_0$ need not to be generic). The tangent space $T_{\gamma_0} Q_{g,m}$ is identified with the first hypercohomology group of the complex of sheaves

\[L^* : \quad 0 \rightarrow \Theta_{M_0} \xrightarrow{L_{q_0}} \Omega_{M_0}^{\otimes 2} \rightarrow 0.\]

The first cochain group is the direct sum $C^0(M_0, \Omega_{M_0}^{\otimes 2}) \oplus C^1(M_0, \Theta_{M_0})$. Consider an appropriate covering $U = \{U_i\}$ on $M_0$ such that $\mathbb{H}^1(L^*) \cong \mathbb{H}^1(U, L^*)$ (see the proof of [17] Proposition 4.5)).

A cochain $\{\phi_i, \{X_{ij}\}_{i,j}\}$ in $C^0(U, \Omega_{M_0}^{\otimes 2}) \oplus C^1(U, \Theta_{M_0})$ is said to be a cocycle if it satisfies

\[(5.4) \quad \delta\{X_{ij}\}_{i,j} = X_{ij} + X_{jk} + X_{ki} = 0, \quad \delta\{\phi_i\}_i = \phi_i - \phi_j = L_{X_{ij}}(\gamma_0).\]

A coboundary is a cochain $\{\phi_i, \{X_{ij}\}_{i,j}\}$ of the form

\[(5.5) \quad X_{ij} = Z_i - Z_j = \delta\{Z_i\}_i, \quad \phi_i = L_{Z_i}(\gamma_0)\]

for some 0-cochain $\{Z_i\}_i \in C^0(U, \Theta_{M_0})$ (cf. Figure 3).

For the hypercohomology class $\{\phi_i, \{X_{ij}\}_{i,j}\} \in \mathbb{H}^1(L^*)$, when the Kodaira-Spencer class of the 1-cochain $\{X_{ij}\}_{i,j}$ is trivial in $H^1(M_0, \Theta_{M_0})$, the hypercohomology class $\{\phi_i, \{X_{ij}\}_{i,j}\}$ is associated to a holomorphic quadratic differential on $M_0$. Indeed, from (5.3) and (5.5),

\[\phi_i - \phi_j = L_{X_{ij}}(\gamma_0) = L_{Z_i}(\gamma_0) - L_{Z_j}(\gamma_0)\]

and $\{\phi_i - L_{Z_i}(\gamma_0)\}_i$ defines a holomorphic quadratic differential on $M_0$. 

The 1-cochain $\{X-\text{infinitesimal Beltrami differential}\}$

5.7. Homomorphisms and hypercohomology classes. From Proposition 4.1, we have a canonical inclusion

\[
\text{Hom}(q_0) \cong T_{q_0}Q(\pi(q)) \hookrightarrow T_{q_0}Q_{g,m} \cong \mathbb{H}^1(L^\bullet).
\]

Let $v \in \text{Hom}(q_0)$ and $\{(\phi_i)_{ij}, \{X_{ij}\}_{i,j}\} \in \mathbb{H}^1(L^\bullet)$ the corresponding hypercohomology class via (5.6). Take a 0-cochain $\{X_i\}_i$ of the sheaf of $C^\infty$-vector fields such that $X_i - X_i = X_{i,j}$ on $U_i \cap U_j$, and each $X_i$ vanishes at any marked point of $M_0$.

The 1-cochain $\{X_{i,j}\}_{i,j}$ defines a holomorphic tangent vector at $x_0$ associated to the infinitesimal Beltrami differential $-(X_i)_{\pi}$ on $M_0$ (cf. [33 (3.6)]). The minus sign comes from our “$i,j$-convention” in the definition of the hypercohomology (compare with Equation (7.27) in [19 §7.2.4]). The holomorphic tangent vector from the 1-cochain $\{X_{i,j}\}_{i,j}$ coincides with the image of $v \in \text{Hom}(q_0)$ via the differential of the projection $Q_{g,m} \rightarrow T_{g,m}$.

After choosing the covering $U = \{U_i\}_i$, appropriately, the right and left sides of the inclusion (5.6) is related to the following formula:

\[
v(C) = \int_C \Omega[q_0, v]
\]

for $C \in H_1(M_{q_0}, \Sigma_{ab}(q_0), \mathbb{R})^-$, where $\Omega[q_0, v]$ is a $C^\infty$-closed 1-form on $\tilde{M}_{q_0}$ defined by

\[
\Omega[q_0, v] = \left( \frac{\phi_i}{2\omega_{q_0}'} - \omega_{q_0}' \tilde{X}_i - \omega_{q_0}(\tilde{X}_i)_z \right) dz - \omega_{q_0}(\tilde{X}_i)_z d\tilde{\pi}
\]

on $U_i$, and tildes in (5.7) mean objects (differentials or vector fields etc.) on the covering space $\tilde{M}_{q_0}$ which obtained as lifts of objects on $M_0$. For a proof, see e.g. [33 Lemma 3.1]. Actually, in [33 Lemma 3.1], we discuss only in the case where $q_0$ is generic. However, we can deduce the same argument since we consider deformations of holomorphic quadratic differentials along strata (see also the discussion in [9 Lemma 5.6]).

Remark 3. We notice the following:

1. Fix $\epsilon > 0$ sufficiently small. Then, $\phi_i$ is the $\lambda$-derivative of the infinitesimal deformation of a holomorphic mapping $\{\lambda | \epsilon < \epsilon \} \ni \lambda \mapsto q(\phi_i, \lambda) \in \mathbb{Q}(\pi(q_0))$ on $U_i$ at $\lambda = 0$ (e.g. [33 §3.3]). Since $q_0(\lambda, \lambda \nu)$ varies in $\mathbb{Q}(\pi(q_0))$, we can see that $a_p(\phi_i) \geq a_p(q_0) - 1$ for $p \in \Sigma_{ab}(q_0) \cap U_i$ and $a_p(\phi_i) \geq a_p(q_0)$ for $p \in \Sigma_{ab}(q_0) \cap U_i$ (cf. [9 Lemma 5.2]). Hence the first term of the coefficient of $dz$ of the differential $\Omega[q_0, v]$ in (5.8) is holomorphic around $\tilde{\Sigma}(q_0) \cap U_i$. 

Figure 3. Double complex for the tangent spaces to $Q_{g,m}$
For $v \in \text{Hom}(q_0)$, we define the complex conjugate $\overline{v} \in \text{Hom}(q_0)$ of $v$ by

$$\overline{v}(C) = \overline{v(C)}$$

for $C \in H_1(\hat{M}_{q_0}, \hat{\Sigma}_{ub}(q_0), \mathbb{R})^-$. We can easily deduce from (5.7) that

$$\int_C \Omega[q_0, \overline{v}] = \int_C \Omega[q_0, v]$$

for $C \in H_1(\hat{M}_{q_0}, \hat{\Sigma}_{ub}(q_0), \mathbb{R})^-$. Notice that the complex conjugate of $v$ here is thought of as a tangent vector in the $(1,0)$-part in the complexification of the real tangent vector space at $q_0$. Compare [24, Proposition 1.5 in Chapter IX].

We claim the following (cf. [8] and [9, Lemma 5.6]).

**Proposition 5.1.** Let $q_0 \in Q_{g,m}$. Let $v \in \text{Hom}(q_0)$ and $\{\{\phi_i\}, \{X_{ij}\}_{i,j}\}$ the corresponding hypercohomology class. When the Kodaira-Spencer class of $\{X_{ij}\}_{i,j}$ is trivial,

$$\Omega[q_0, v] = \frac{\pi_0^*(\psi)}{\omega_{q_0}}$$

for some $\psi \in Q^T_{x_0}(q_0)$.

**Proof.** The assumption implies that there is a 0-cochain $\{Z_i\}_i \in C^0(\mathcal{U}, \Theta_{M_0})$ such that $Z_i - Z_j = X_{ij}$ from (5.8) we have

$$\Omega[q_0, v] = \left(\frac{\phi_i}{2\omega_{q_0}} - \omega'_{q_0} \tilde{Z}_i - \omega_{q_0} \tilde{Z}'_i\right) dz = \frac{\psi_i}{2\omega_{q_0}} dz$$

where

$$\psi_i = \phi_i - L_{Z_i}(q_0) = \phi_i - (q_0^*Z_i + 2q_0Z'_i).$$

As discussed in the last paragraph of (5.6) $\{\psi_i\}_i$ defines a holomorphic quadratic differential $\psi$ on $M_0$. We can check from (1) in Remark 3 and (5.10) that $\psi \in Q^T_{x_0}(q_0)$.

**Proposition 5.2 (Hodge-Kodaira decomposition).** Let $x_0 = (M_0, f_0) \in T_{g,m}$. Suppose $q_0 \in Q_{x_0}$ is generic. For $v \in \text{Hom}(q_0) \cong T_{q_0}Q_{g,m}$, let $v(v, q_0) \in T_{x_0}T_{g,m}$ be the image of $v$ of the differential of the projection $Q_{g,m} \to T_{g,m}$ at $q_0$. Then,

$$v(C) = \int_C \frac{\pi_{q_0}^* (\eta_{v(q_0)})}{\omega_{q_0}} + \int_C \frac{(\pi_{q_0}^* (\eta_{v(v, q_0)}))}{\omega_{q_0}}$$

for $C \in H_1(\hat{M}_{q_0}, \mathbb{R})^- = H_1(\hat{M}_{q_0}, \hat{\Sigma}_{ub}(q_0), \mathbb{R})^-.$

**Proof.** From the definition of the $q_0$-realizations, for $\phi \in Q_{x_0},$

$$\int_{M_0} \mu \phi = \int_{M_0} \frac{\eta_{v(v, q_0)}}{|q_0|} \phi = \frac{1}{2} \int_{\hat{M}_{q_0}} \frac{\pi_{q_0}^* (\eta_{v(v, q_0)})}{|\omega_{q_0}|^2} \pi_{q_0}^* (\phi)$$

$$= -\frac{\sqrt{-1}}{4} \int_{\hat{M}_{q_0}} \left(\frac{\pi_{q_0}^* (\eta_{v(v, q_0)})}{\omega_{q_0}}\right) \land \frac{\pi_{q_0}^* (\phi)}{\omega_{q_0}}.$$

Let $\Omega[q_0, v]^{(0,1)}$ is the $(0,1)$-part of $\Omega[q_0, v]$. From (5.8), a Beltrami differential $\Omega[q_0, v]^{(0,1)}/\omega_{q_0}$ on $\hat{M}_{q_0}$ is the lift of the infinitesimal Beltrami differential $\mu$ on
then, from (5.12), we have
\[
\int_{M_0} \mu \phi = \frac{1}{2} \int_{\tilde{M}_0} \frac{\Omega [\phi, \nu]}{\omega} \pi^*_{q_0} (\phi) = - \frac{\sqrt{-1}}{4} \int_{M_0} \Omega [\phi, \nu] \wedge \frac{\pi^*_{q_0} (\phi)}{\omega_{q_0}}.
\]

We can easily check that every holomorphic 1-form in the \((-1)\)-eigenspace of the space of holomorphic 1-forms is presented as \(\pi^*_{q_0} (\phi) / \omega_{q_0}\) for some \(\phi \in Q_{x_0}\). From (5.11) and (5.12), we have \(\Omega^h = \pi^*_{q_0} (\eta (\nu, q_0)) / \omega_{q_0}\). Since the harmonic differential in the de Rham cohomology class is unique, from (5.9), we deduce that \(\Omega^h = \pi^*_{q_0} (\eta (\nu, q_0)) / \omega_{q_0}\). \(\square\)

For a generic differential \(q_0 \in Q_{g,m}\), we define
\[
\text{Hom}_0 (q_0) = \{ \nu \in \text{Hom}(q_0) \mid \nu (\nu, q_0) = 0 \}.
\]

From Proposition 5.2, we have

**Corollary 5.1.** Let \(x_0 \in T_{g,m}\) and \(q_0 \in Q_{x_0}\) a generic differential. Then, the mapping
\[
\text{Hom}_0 (q_0) \ni \nu \mapsto \eta (\nu, q_0) \in Q_{x_0}
\]
is a complex linear isomorphism.

**Example 4.** For generic \(q \in Q_{g,m}\),
\[
\int_C \pi^*_{q_0} (u) \omega_q = \int_C \omega_q = u [q] (C) = \int_C \frac{\pi^*_{q_0} (\eta (u [q], q))}{\omega_q} + \frac{\pi^*_{q_0} (\eta (u [q], q))}{\omega q}.
\]

for \(C \in H_1 (M, \mathbb{R})\). Therefore, \(\eta (u [q], q) = q\) and \(\eta (u [q], q) = 0\).

6. **Stratifications of Teichmüller space**

6.1. **Stratifications on \(Q_{x_0}\).** Let \(x_0 \in T_{g,m}\), Dumas [9] defined a stratification of \(Q_{x_0}\) by symbols applying the Whitney stratification (cf. [10] and [35]). Indeed, the stratification on \(Q_{g,m}\) provides a stratification on \(Q_{x_0}\) by complex-analytic sets. This stratification can be refined as a complex-analytic stratification \(\{ Z_i \}_{i \in I} = \{ Z_i, x_0 \}_{i \in I}\) satisfying the following conditions:

1. Each \(Z_i\) is a complex submanifold of \(Q_{x_0} \setminus \{ 0 \}\) invariant under the action of \(C^*\);
2. the symbol is constant on each stratum \(Z_i\);
3. \(Q_{x_0} \setminus \{ 0 \} = \cup_{i \in I} Z_i\);
4. \(Z_i \cap Z_j = \emptyset\) if \(i \neq j\);
5. the closure \(Z_j\) is a complex-analytic set, and if \(Z_i \cap \overline{Z_j} \neq \emptyset\) for \(i, j \in I\), then \(Z_i \subset \overline{Z_j}\).

The refinement refers to changing the stratification in such a way that each new stratum is entirely contained in one of the old strata. Under the situation in the above (5), \(\dim_c Z_i < \dim_c Z_j\) if \(Z_i \neq Z_j\). There is a unique stratum \(Z_\infty\) consisting of all generic differentials (we assume the index set \(I\) contains a symbol \(\infty\)). Since the stratification is locally finite, we have
Lemma 6.1. For any \( q_0 \in Z_i - \{0\} \), there is a neighborhood \( U \) in \( Q_{x_0} - \{0\} \) of \( q_0 \) such that \( I_U = \{i \in I \mid Z_i \cap U \neq \emptyset\} \) is a finite set; and if \( Z_j \cap U \neq \emptyset \), then \( Z_i \cap Z_j \neq \emptyset \).

We extend an observation by Dumas as follows (cf. Lemma 5.2 in \cite{9}).

Proposition 6.1 (Tangent space to the strata in fibers). Let \( \{Z_i\}_{i \in I} \) is the stratification of \( Q_{x_0} \) defined in (6.1). Let \( q_0 \in Z_i \). If we identify the tangent space \( T_{q_0}Z_i \) as a subspace of \( Q_{x_0} \), we have \( T_{q_0}Z_i \subset Q_{x_0}^T(q_0) \).

Proof. Let \( p_0 \in \Sigma_s(q_0) \) and \( k_0 = o_{p_0}(q_0) \). For simplicity, \( q_0 \) is assumed to be represented as \( q_0 = z^{k_0}dz^2 \) around \( p_0 \) with the coordinate \( z \) with \( z(p_0) = 0 \). From the universal deformation of the singularities, the deformation of \( q_0 \) around \( p_0 \) is described as the Lie derivative

\[
L_X(z^{k_0}dz^2) = (k_0z^{k_0-1}X(z) + 2z^{k_0}X'(z))dz^2
\]

along a holomorphic vector field \( X = X(z)(\partial/\partial z) \) around \( p_0 \), where \( X(0) = 0 \) if \( p_0 \in \Sigma_m(q_0) \) (cf. \cite{17} Proposition 3.1). See also Lemma 5.2 in \cite{9}). One can see that the infinitesimal deformation \( \dot{q} \) satisfies

\[
o_{p_0}(\dot{q}) = \begin{cases} k_0 - 1 & \text{(if } p_0 \in \Sigma_s\setminus\Sigma_m(q_0)\text{)} \\ k_0 & \text{(if } p_0 \in \Sigma_m(q_0)\text{)} \end{cases}
\]

and is contained in \( Q_{x_0}^T(q_0) \). \( \square \)

6.2. Stratification of Teichmüller space. Let \( x_0 \in T_g,m \). Let \( \{Z_i\}_{i \in I} \) be the stratification of \( Q_{x_0} - \{0\} \) defined in (6.1). Let \( U_{Q_{x_0}} \) be the unit ball in \( Q_{x_0} \) with respect to the \( L^1 \)-norm and set \( \Xi_{x_0}: U_{Q_{x_0}} \rightarrow T_{g,m} \) be the Teichmüller homeomorphism discussed in \cite{2, 2, 2} For \( i \in I \), we define \( T_i = \Xi_{x_0}(Z_i \cap U_{Q_{x_0}}) \). The purpose of this section is to show the following.

Theorem 5 (Stratification). The collection \( \{T_i\}_{i \in I} \) is a stratification of real-analytic submanifolds in \( T_{g,m} - \{x_0\} \).

Since \( \Xi_{x_0} \) is a homeomorphism, \( \{T_i\}_{i \in I} \) is a stratification of topological manifolds in \( T_{g,m} - \{x_0\} \). Namely, each \( T_i \) is a locally closed topological submanifold of \( T_{g,m} - \{0\} \), the collection \( \{T_i\}_{i \in I} \) is a locally finite and satisfies

\[
(3') T_{g,m} - \{0\} = \bigsqcup_{i \in I} T_i;
(4') T_i \cap T_j = \emptyset \text{ if } i \neq j; \text{ and }
(5') T_i \cap T_j \neq \emptyset \text{ for } i, j \in I, \text{ then } T_i \subset T_j.
\]

(The numbers correspond to those in the properties of complex-analytic stratifications given in \cite{6, 1}.) We will show that the restriction of \( \Xi_{x_0} \) to each \( Z_i \) is a real-analytic immersion. The author does not know if the closure \( \overline{T_i} \) is a real-analytic subset of \( T_{g,m} - \{0\} \) for each \( i \in I \). Notice that Theorem 5 is recognized as a kind of refinements of Masur’s result \cite[Proposition 2.2]{30}.)

Proof of Theorem 5. Let \( i \in I \). Notice from the definition that \( Z_i \) is a complex submanifold of \( Q_{x_0} \). From \cite{2, 2} and \cite{3, 3} the Teichmüller homeomorphism \( \Xi_{x_0} \) on \( Z_i \) is described as

\[
\Xi_{x_0}(q) = \Pi(Q[tanh^{-1}(\|q\|), q])
\]
for \( q \in Z \cap U_{\mathcal{Q} x_0} \). From Proposition 1.1 and Riemann’s formula, the norm \( Z \ni q \mapsto |q| \) varies real-analytically (cf. [26, §1] and [11, Chapter III]). Hence the mapping

\[
Z \ni q \mapsto \mathcal{Q} [\tan^{-1}(||q||), q] \in \mathcal{Q}(\pi(q))
\]

is real-analytic. Therefore, \( \Xi_{x_0} \) is also real-analytic on \( Z \), since \( \Pi \) is holomorphic. Hence, to complete the proof, it suffices to show that the (real) differential of the restriction of \( \Xi_{x_0} \) to \( Z \) is non-singular.

Let \( q_0 \in Z \cap U_{\mathcal{Q} x_0} \) and \( v \in \text{Hom}(q_0) \) (\( \mapsto T_{q_0} \mathcal{Q}(\pi(q_0)) \)) which tangent to \( Z \). For simplicity, set \( Q_0 = \mathcal{Q}[\tan^{-1}(||q_0||), q_0] \) and \( x_1 = (M_1, J_1) = x_{\tan^{-1}(||q_0||), q_0} \in T_{g, m} \) (cf. 5.4). From Proposition 6.1, there is \( \psi \in \mathcal{Q}_{x_0}^T(q_0) \) such that

\[
(6.1) \quad v(C) = \int_C ^{Q_{x_0}}(\psi) \omega_{q_0}
\]

for \( C \in H_1(M_{q_0}, \Sigma_{u}(q_0), \mathbb{R})^- \).

Let \( f: \{||\lambda|| < \epsilon\} \rightarrow Z \) be a holomorphic disk with \( q(0) = q_0 \) and \( q'(0) = v \). For simplicity, set \( K(0) = \exp(2 \tan^{-1}(||q(t)||)) = (1 + ||q(t)||/(1 - ||q(t)||)) \) for \( t \in \mathbb{R} \) with \( |t| < \epsilon \). From (5.3) and (6.1),

\[
(6.2) \quad \frac{d}{dt}{|_{t=0}} \bigg| u(\mathcal{Q}[\tan^{-1}(||q(t)||), q(t)])(C) = \text{Re} \int_C ^{Q_{x_0}}(\psi) \omega_{q_0} + \sqrt{-1} \text{Im} \left( K(0)^{-1} \int_C ^{Q_{x_0}}(\psi) \omega_{q_0} + (K^{-1})'_{|t=0} \int_C \omega_{q_0} \right).
\]

for \( C \in H_1(M_{q_0}, \Sigma_{u}(q_0), \mathbb{R})^- \).

Recall that the holomorphic tangent space is the \((1, 0)\)-part of the complexification of the real tangent vector space (cf. [24, Chapter IX]). In general, for a complex manifold with a local chart \( z = (z_1, \cdots, z_n) \), a holomorphic tangent vector \( \sum_{j=1}^n a_j(\partial/\partial z_j) \) is the \((1, 0)\)-part of a real tangent vector \( \sum_{j=1}^n (a_j(\partial/\partial z_j) + \pi_j(\partial/\partial \overline{z}_j)) \) of the underlying differential structure. The variation \( \mathbf{w} \) stands for the \((1, 0)\)-part of the image of the corresponding real tangent vector to \( v \) under the (real) differential of the map \( Z \ni q \mapsto \mathcal{Q}[\tan^{-1}(||q||), q] \in \mathcal{Q}(\pi(q)) \) around \( q_0 \). We denote by \( \mathbf{w}(C) \) the right-hand side of (6.2). Then, \( \mathbf{w} \) stands for a homomorphism in \( \text{Hom}(Q_0) \) (\( \subset T_{Q_0} \mathcal{Q}(\pi(q_0)) \)) via the isomorphism \( H_1(M_{q_0}, \Sigma_{u}(q_0), \mathbb{R})^- \cong H_1(M_{Q_0}, \Sigma_{u}(Q_0), \mathbb{R})^- \) induced by the Teichmüller mapping from \( x_0 \) to \( x_1 \).

Suppose that the derivative

\[
\{(t) < \epsilon \mid t \in \mathbb{R}\} \ni t \mapsto \Pi (Q[tan^{-1}(||q(t)||), q(t)])
\]

at \( t = 0 \) vanishes. We will conclude \( \mathbf{w} = 0 \).

Since \( \Pi \) is holomorphic, the differential of \( \Pi \) sends the \((1, 0)\)-part \( T_{Q_0} Q_{x_0} \) of the complexification of the real tangent space at \( Q_0 \) to that at \( x_1 \). From the assumption, we deduce \( \nu(\mathbf{w}, Q_0) = 0 \) in \( T_{x_2} T_{g, m} \) (cf. [24, Proposition 2.9, Chapter IX]). From Proposition 5.1, there is \( \phi \in \mathcal{Q}^T_{x_1}(Q_0) \) such that

\[
(6.3) \quad \mathbf{w}(C) = \int_C ^{Q_{x_0}}(\phi) \omega_{Q_0}
\]

for \( C \in H_1(M_{q_0}, \Sigma_{u}(q_0), \mathbb{R})^- \cong H_1(M_{Q_0}, \Sigma_{u}(Q_0), \mathbb{R})^- \).

Let \( \psi \in \mathcal{Q}_{x_0}^T \) and \( \phi' \in \mathcal{Q}_{x_0}^T \), be the holomorphic quadratic differentials defined by descending the squares \( (\pi^*_{x_0}(\psi)/\omega_{q_0})^2 \) and \( (\pi^*_{Q_0}(\phi)/\omega_{Q_0})^2 \) respectively. Comparing
the real parts of (6.2) and (6.3) we have \( \nu(\phi') = \nu(\psi') \) in \( \mathcal{MF} \) (cf. [17] Lemma 4.3). Since \( K(0) = e^{2d_F(x_0,x_0)} \),

(6.4) \[ K(0)^{-1}\|\psi'\| = e^{-2d_F(x_0,x_0)}\text{Ext}_{x_0}(\nu(\psi')) \leq \text{Ext}_{x_0}(\nu(\phi')) = \|\phi'\| \]

from the Kerckhoff formula (see also [13] Lemma 4.1).

By Riemann’s formula, (6.3) and (6.4),

(6.5) \[ \|\phi'\| = \frac{1}{2} \int_{\tilde{M}_{q_0}} \text{Re} \left( \frac{\pi_{q_0}^* (\phi)}{\omega_{q_0}} \right) \wedge \text{Im} \left( \frac{\pi_{q_0}^* (\phi)}{\omega_{q_0}} \right) \]

(6.6) \[ = K(0)^{-1} \frac{1}{2} \int_{\tilde{M}_{q_0}} \text{Re} \left( \frac{\pi_{q_0}^* (\psi)}{\omega_{q_0}} \right) \wedge \text{Im} \left( \frac{\pi_{q_0}^* (\psi)}{\omega_{q_0}} \right) \]

\[ + (K^{-1})'|_{t=0} \frac{1}{2} \int_{\tilde{M}_{q_0}} \text{Re} \left( \frac{\pi_{q_0}^* (\psi)}{\omega_{q_0}} \right) \wedge \text{Im}(\omega_{q_0}) \]

\[ = K(0)^{-1}\|\psi'\| + (K^{-1})'(0) \text{Re} \left\{ \frac{\sqrt{-1}}{4} \int_{\tilde{M}_{q_0}} \frac{\pi_{q_0}^* (\psi)}{\omega_{q_0}} \wedge \omega_{q_0} \right\} . \]

Since

(6.7) \[ \frac{d\|q(t)\|}{dt} \bigg|_{t=0} = \text{Re} \left\{ \frac{\sqrt{-1}}{2} \int_{\tilde{M}_{q_0}} \frac{\pi_{q_0}^* (\psi)}{\omega_{q_0}} \wedge \omega_{q_0} \right\} , \]

from (6.4) and (6.5), we obtain

\[ 0 \leq \|\phi'\| - K(0)^{-1}\|\psi'\| = (K^{-1})'(0) \text{Re} \left\{ \frac{\sqrt{-1}}{4} \int_{\tilde{M}_{q_0}} \frac{\pi_{q_0}^* (\psi)}{\omega_{q_0}} \wedge \omega_{q_0} \right\} \]

\[ = - \frac{1}{(1 + \|q_0\|)^2} \left( \frac{d\|q(t)\|}{dt} \bigg|_{t=0} \right)^2 , \]

and \( (K^{-1})' = 0 \) at \( t = 0 \). Therefore, \( \|\phi'\| = K(0)^{-1}\|\psi'\| \) from (6.5) again. Hence, we have \( \nu(\psi') = s\nu(q_0) \) and \( \psi' = s^2 q_0 \) for some \( s \geq 0 \) from the uniqueness of the extremal problem for the Kerckhoff formula (or the Teichmüller uniqueness theorem. See [19] Theorem 5.9) or [11] (3.5)). From (6.7), we obtain

\[ 0 = \frac{d\|q(t)\|}{dt} \bigg|_{t=0} = s^2\|q_0\| \]

and \( s = 0 \). Therefore, \( \psi' = 0 \) and \( \nu = 0 \) from (6.1). \( \square \)

From (6.2), we conclude the following.

**Corollary 6.1.** The Teichmüller distance function \( T_{g,m} \setminus \{ x_0 \} \ni x \mapsto d_T(x_0,x) \) is real-analytic on each stratum of \( \{ T_i \}_{i \in I} \).

Recall that the top stratum \( Z_\infty \) of the stratification of \( \mathcal{Q}_{x_0} \) is an open set which consists of generic differentials. From Theorem 5 the restriction of the Teichmüller homeomorphism \( \Xi_{x_0} : Z_\infty \to T_\infty \) is a real-analytic diffeomorphism. Hence, Corollary 6.1 is thought of as an extension of an observation by Rees in [38] §2.3.
6.3. Non-generic strata are removable. Let us prove Theorem 2. We use the following removable singularity theorem due to Blanchet (see also [5]).

Proposition 6.2 (Blanchet [2]). Let \( \Omega \) be a domain in \( \mathbb{C}^N \) and \( V \subset \Omega \) be a \( C^1 \)-real submanifold with positive real codimension. Let \( u \) be a function of class \( C^1 \) on \( \Omega \). Then, \( u \) is plurisubharmonic on \( \Omega \) if so is \( u \) on \( \Omega - V \).

We return to our setting. Let \( \{ T_{g,m} \}_{i \in I} \) be the stratification in Theorem 5. Let \( u \) be a function of class \( C^1 \) on \( T_{g,m} - \{ x_0 \} \) which is bounded above around \( x_0 \). Suppose that \( u \) is plurisubharmonic on the top stratum \( T_\infty \).

Let \( x_1 \in T_{g,m} - \{ x_0 \} \) and \( T_i \) the stratum containing \( x_1 \). Suppose that \( u \) is extended as a plurisubharmonic function on \( T_j \) for all \( j \in I \) with \( \dim T_j > \dim T_i \). From the locally finiteness of the stratification, there is a small neighborhood \( U \) of \( x_1 \) such that \( I(U) = \{ j \in I \mid T_j \cap U \neq \emptyset \} \) is a finite set and \( \overline{I(T_j \cap U)} \neq \emptyset \) for \( j \in I(U) \) from Lemma 6.1. From the assumption, \( u \) is plurisubharmonic on \( U - T_i \). Since \( T_i \) is a real-analytic submanifold of \( T_{g,m} \) with positive codimension, by Blanchet’s extension theorem (Proposition 6.2), \( u \) is plurisubharmonic on \( U \). This inductive procedure guarantees that \( u \) is plurisubharmonic on \( T_{g,m} - \{ x_0 \} \). Since \( u \) is bounded above around \( x_0 \), \( u \) is extended as a plurisubharmonic function on \( T_{g,m} \) (cf. [23] Theorem 2.9.22).

7. Pluricomplex Green function on the Teichmüller space

In this section, we will show the following theorem which implies Theorem 2 since the Teichmüller distance is the Kobayashi distance on \( T_{g,m} \) (cf. [39] and [41]).

Theorem 6 (Plurisubharmonicity). Let \( x_0 \in T_{g,m} \). The log-tanh of the Teichmüller distance function

\[ T_{g,m} \ni x \mapsto u_{x_0}(x) := \log \tanh d_T(x_0, x) \]

is plurisubharmonic on \( T_{g,m} \).

Earle [10] showed that \( u_{x_0} \) is of class \( C^1 \) on \( T_{g,m} - \{ x_0 \} \). Since \( u_{x_0}(x) \to -\infty \) as \( x \to x_0 \), from Theorem 2, it suffices to show that \( u_{x_0} \) is plurisubharmonic on the top stratum \( T_\infty \).

7.1. Complex analysis. Let \( X \) be a complex manifold. Let \( p \in X \) and \( z = (z_1, \ldots, z_n) \) be a holomorphic local chart around \( p \). Let \( u \) be a \( C^2 \) function around \( p \) on \( X \). For \( v = \sum_{i=1}^{n} v_i(\partial / \partial z_i) \in T_p X \), we define the Levi form of \( u \) by

\[ \mathcal{L}(u)[v, \overline{v}] = \sum_{i,j=1}^{n} \frac{\partial^2 u}{\partial z_i \partial z_j}(z(p)) v_i \overline{v_j}. \]

Let \( g : \{ \lambda \in \mathbb{C} \mid |\lambda| < \epsilon \} \to X \) be a holomorphic mapping with \( g(0) = p \) and \( g_* (\partial / \partial \lambda) = v \). Then, we see

\[ \mathcal{L}(u)[v, \overline{v}] = \frac{\partial^2 (u \circ g)}{\partial \lambda \partial \overline{\lambda}}(0). \]

A \( C^2 \) function \( u \) on \( X \) is called plurisubharmonic if \( \mathcal{L}(u)[v, \overline{v}] \geq 0 \) for \( v \in T_p X \) and \( p \in X \). In general, a function \( u \) on a domain \( \Omega \) on \( \mathbb{C}^N \) is called plurisubharmonic if for any \( a \in \Omega \) and \( b \in \mathbb{C}^N \), \( \lambda \mapsto u(a + \lambda b) \) is subharmonic or identically \(-\infty \) on every component of \( \{ \lambda \in \mathbb{C} \mid a + \lambda b \in \Omega \} \).
A bounded domain $\Omega$ in $\mathbb{C}^n$ is said to be hyperconvex if it admits a negative continuous plurisubharmonic exhaustion (cf. [41]). Krushkal [27] showed that Teichmüller space is hyperconvex (see also [33]).

Demainly [16] observed that for any bounded hyperconvex domain $\Omega$ in $\mathbb{C}^n$ and $w \in \Omega$, there is a unique plurisubharmonic function $g_{\Omega,w} : \Omega \to (-\infty, 0)$ such that

1. $(dd^c g_{\Omega,w})^n = (2\pi)^n \delta_w$, where $\delta_w$ is the Dirac measure with support at $w$; and
2. $g_{\Omega,w}(z) = \sup_v \{ v(z) \}$ where the supremum runs over all non-negative plurisubharmonic functions $v$ on $\Omega$ with $v(z) \leq \log \|z - w\| + O(1)$ around $z = w$.

(see also [67, Théorème 4.3]). The function $g_{\Omega}(w,z) = g_{\Omega,w}(z)$ is called the pluricomplex Green function on $\Omega$.

Klimek showed that

\[ \log \tanh \text{Car}_\Omega(z, w) \leq g_{\Omega}(z, w) \leq \log \tanh \text{Kob}_\Omega(z, w) \]

for $z, w \in \Omega$ and the equality in the second inequality in (7.2) holds if the third term of (7.2) is plurisubharmonic, where Car$\Omega$ and Kob$\Omega$ are the Carathéodory distance and the Kobayashi distance on $\Omega$, respectively (cf. [22, Corollaries 1.2 and 1.4]).

7.2. Setting. Let $q_0 \in Z_\infty \cap Q_{x_0}$ and $x_1 = \Xi_{x_0}(q_0)$. Let $v \in T_{x_1} T_{g,m}$ and $g : \{ |\lambda| < \epsilon \} \to T_{x_1}$ a holomorphic mapping with $g(0) = 0$ and $g(\partial/\partial \lambda|_{\lambda=0}) = v$. For the simplicity, let

\[ q_{\lambda} = \Xi^{-1}_{x_0}(g(\lambda)) \in Z_\infty \subset Q_{x_0}, \]
\[ Q_{\lambda} = Q[\tanh^{-1}(\|q_{\lambda}\|), q_{\lambda}] \in Q_{g(\lambda)}, \]
\[ d(\lambda) = d_T(x_0, g(\lambda)), \text{ and } d_0 = d(0) = d_T(x_0, x_1) \]

for $\lambda \in \{ |\lambda| < \epsilon \}$. Notice again that each $Q_{\lambda}$ is generic since the Teichmüller mapping preserves the order of singular points. For calculations later, we notice from the definition that

\[ \|q_{\lambda}\| = \tanh(d(\lambda)) \text{ and } \|Q_{\lambda}\| = e^{-2d(\lambda)}\|q_{\lambda}\|. \]

7.2.1. We define $v_1, v_2 \in \text{Hom}(q_0) (\cong T_{q_0} Q_{g,m})$ by

\[ u[q_{\lambda}] = u[q_0] + \lambda v_1 + \bar{\lambda} v_2 + o(|\lambda|) \]

as $\lambda \to 0$ on $H_1(M_{q_0}, \mathbb{R})^- \cong H_1(M_{q_0}, \Sigma_{ub}(q_0), \mathbb{R})^-$. Since $q_{\lambda} \in Q_{x_0}$ for all $\lambda$, we deduce $v(v_1, q_0) = 0$ for $i = 1, 2$ and $v_1, v_2 \in \text{Hom}(q_0) (\cong Q_{x_0} \subset T_{q_0} Q_{g,m})$. We will use the notation

\[ d_{x_1}(v) = v_1, \text{ and } d_{\bar{x}_1}(v) = v_2 \]

after calculating the first derivative and the Levi form of the Teichmüller distance (cf. [74, 76]). However, in the following calculation, we will use the notation $v_1$ and $v_2$ for the simplicity.

From (7.2) and (7.4),

\[ u[Q_{\lambda}] = \text{Re}(u[q_{\lambda}]) + \sqrt{-1}e^{-2d(\lambda)}\text{Im}(u[q_{\lambda}]) \]
\[ = u[q_0] + \lambda w_1 + \bar{\lambda} w_2 + o(|\lambda|) \]
on $H_1(M_{q_0}, \mathbb{R})^-$ as $\lambda \to 0$, where $w_1$ and $w_2$ are in $\text{Hom}(q_0)$ defined by

\[
\begin{cases}
  w_1 = \frac{1 + e^{-2d_0}}{2} v_1 + \frac{1 - e^{-2d_0}}{2} v_2 - d_\lambda e^{-2d_0}(u[q_0] - u[q]) \\
  w_2 = \frac{1 - e^{-2d_0}}{2} v_1 + \frac{1 + e^{-2d_0}}{2} v_2 - d_\lambda e^{-2d_0}(u[q_0] - u[q]),
\end{cases}
\]

where $d_\lambda$ is the $\lambda$-derivative of the Teichmüller distance function $d(\lambda)$ at $\lambda = 0$.

In (7.6), we canonically identify $\text{Hom}(Q_0)$ with $\text{Hom}(q_0)$, and $w_1$ and $w_2$ stands for tangent vectors in $T_{Q_0} Q_{g,m} \cong \text{Hom}(Q_0)$, while the right-hand sides of (7.6) are tangent vectors in $\text{Hom}(q_0) \cong T_{q_0} Q_{g,m}$. See the discussion in the proof of Theorem 5 and (2) of Remark 3.

Since $\Pi(u[Q_\lambda]) = g(\lambda)$, we have

\[
v(w_1, Q_0) = v \quad \text{and} \quad v(w_2, Q_0) = 0
\]

and $w_2 \in \text{Hom}_0(Q_0)$, since $\Pi$ is holomorphic.

7.2.2. Since $H_1(M_{q_0}, \mathbb{R})^- \cong H_1(M_{q_0}, \Sigma_{ab}(q_0), \mathbb{R})^-$, $\text{Hom}(q_0)$ is canonically isomorphic to the cohomology group $H^1(M_{q_0}, \mathbb{R})^-$. We define the wedge product $\wedge$ on $\text{Hom}(q_0)$ by

\[
x \wedge y = \int_{M_{q_0}} \frac{\pi_{q_0}^*(\eta_{x(y,q_0)})}{\omega_{q_0}} \wedge \left( \frac{\pi_{q_0}^*(\eta_{y(y,q_0)})}{\omega_{q_0}} \right) - \frac{\pi_{q_0}^*(\eta_{y(x,q_0)})}{\omega_{q_0}} \wedge \left( \frac{\pi_{q_0}^*(\eta_{x(y,q_0)})}{\omega_{q_0}} \right)
\]

for $x, y \in \text{Hom}(q_0)$. For generic $q \in Q_{g,m}$,

\[
\sqrt{-1} u[q] \wedge \overline{u[q]} = 4 \|q\|
\]

(cf. (2.2) and Example 4).

**Example 7** (Teichmüller disk). The Teichmüller disk associated to $q_0$ is defined as an isometric holomorphic disk in $T_{q_0}$ defined by the holomorphic family of Beltrami differentials

\[
\mathbb{D} \ni \lambda \mapsto \left( \frac{\lambda + \tanh(d_0)}{1 + \tanh(d_0) \lambda} \right) \frac{q_0}{\|q_0\|}
\]

on $M_0$. With the Teichmüller homeomorphism (2.1), the Teichmüller disk is described as

\[
\mathbb{D} \ni \lambda \mapsto \Xi_{x_0} \left( \left( \frac{\lambda + \tanh(d_0)}{1 + \tanh(d_0) \lambda} \right) \frac{q_0}{\|q_0\|} \right).
\]

For $\lambda \in \mathbb{D}$, let $D_{q_0}(\lambda)$ be the right-hand side of (7.9). By definition, $D_{q_0}(0) = x_1$ and $D_{q_0}(-\tanh(d_0)) = x_0$. Then

\[
u \Xi_{x_0}^{-1}(D_{q_0}(\lambda)) = \left( \frac{\lambda + \tanh(d_0)}{1 + \tanh(d_0) \lambda} \right)^{1/2} u[q_0]
\]

\[= u[q_0] + \frac{\lambda}{\sinh(2d_0)} u[q_0] + o(|\lambda|),
\]

where the branch of the square root taken to be $1^{1/2} = 1$. 
PLURIPOTENTIAL THEORY ON TEICHMÜLLER SPACE I– PLURICOMPLEX GREEN FUNCTION

7.3. **The first variation of the Teichmüller distance.** We give the first variational formula of the Teichmüller distance function in our setting. From Riemann’s formula, (7.3) and (7.8), we deduce

\[
d_\lambda = (\tanh^{-1}(|q|_\lambda))_{\lambda=0} = \frac{1}{1 - ||q_0||^2} \left( \frac{\sqrt{-1}}{4} (v_1 \wedge \overline{u[q_0]} + u[q_0] \wedge v_2) \right)
\]

(7.11)

where \(u\) is the infinitesimal Beltrami differential on \(M_1\) representing \(v\). From (7.3), (7.7) and (7.8), we have

\[
d_\lambda = \frac{1}{2||Q_0||} \int_{M_1} \mu Q_0
\]

On the other hand, Earle [10] gave the first variational formula

\[
d_\lambda = \frac{1}{2||Q_0||} \int_{M_1} \mu Q_0 = -\frac{1}{2e^{-2d_0} \tanh(d_0)} \int_{M_0} \frac{1}{|Q_0|} \nabla^* Q_0 - \frac{\sqrt{-1} e^{2d_0}}{8 \tanh(d_0)} (v_1 \wedge u[q_0] + u[q_0] \wedge v_2) - d_\lambda e^{-2d_0} (u[q_0] - u[\overline{q_0}])
\]

(7.12)

Therefore, we obtain

\[
d_\lambda = \frac{\sqrt{-1} \cosh^2(d_0)}{4} \left( -v_1 \wedge \overline{u[q_0]} + u[q_0] \wedge v_2 \right).
\]

Thus, from (7.11) and (7.12) we conclude the following.

**Lemma 7.1** (First variational formula). Under the notations in (7.2) we have

\[
d_\lambda = \frac{\sqrt{-1} \cosh^2(d_0)}{4} u[q_0] \wedge v_2
\]

and \(v_1 \wedge \overline{u[q_0]} = 0\).

7.4. **Levi form of \(d\bar{r}\).** Let \(u[q_\lambda] \in \text{Hom}(q_0)\) be the \(\lambda\)-derivative of the family \(\{u[q_\lambda]\}_{\lambda<\epsilon}\) of the representation. Namely, \(u[q_\lambda](C) = (u[q_\lambda](C))_\lambda\) for \(C \in H_1(M_{q_0}, \mathbb{R})^\perp\). Notice from the notation in (7.2) that \(u[q_\lambda] = v_1\) at \(\lambda = 0\). We also
define \( u_1[q, \lambda] \) and \( u_2[q, \lambda] \) in the same manner. From Lemma 7.1, the \( \lambda \)-derivative of \( d(\lambda) = d_T(x_0, g(\lambda)) \) on a disk \( \{ |\lambda| < \epsilon \} \) is rewritten as
\[
d_{\lambda}(\lambda) = \frac{-\sqrt{-1} \cosh(2d(\lambda))}{4} u[q, \lambda] \wedge \overline{u[q, \lambda]}.
\]
Therefore,
\[
d_{\lambda^X}(0) = \frac{-\sqrt{-1}}{4} \cdot 2 \sinh(d_0) \cosh(d_0) \cdot u[q_0] \wedge \overline{v_2} + \frac{-\sqrt{-1} \cosh^2(d_0)}{4} v_2 \wedge \overline{v_2} + \frac{-\sqrt{-1} \cosh^2(d_0)}{4} u[q_0] \wedge \overline{u[q_0] \lambda^X}_{\lambda=0}.
\]
From Lemma 7.4 again,
\[
0 = (u[q_\lambda] \wedge \overline{u[q_\lambda \lambda]})_{\lambda} = u[q_\lambda] \wedge \overline{u[q_\lambda \lambda]} + u[q_\lambda] \wedge \overline{u[q_\lambda \lambda^X]}
\]
Thus, the Laplacian \( d_{\lambda^X}(0) \) of the distance function \( d(\lambda) \) at \( \lambda = 0 \) is
\[
(7.13) \quad \frac{\cosh^3(d_0) \sinh(d_0)}{8} u[q_0] \wedge \overline{v_2}^2 + \frac{-\sqrt{-1} \cosh^2(d_0)}{4} (v_2 \wedge \overline{v_2} - v_1 \wedge \overline{v_1}).
\]

7.5. **Complex tangent spaces of the spheres.** We use the notation (7.5). Notice that
\[
T_{x_1}, T_{g, m} \ni v \mapsto x_1 + d_T(x_0, x) \quad \text{at} \quad x_1 \in T_{g, m} \setminus \{x_0\}
\]
are complex and anti-complex linear respectively.

From (7.1), Lemma 7.1, and (7.13), the first derivative and the Levi form of the Teichmüller distance function \( T_{g, m} \ni x \mapsto d_T(x_0, x) \) at \( x_1 \in T_{g, m} \setminus \{x_0\} \) are rewritten as
\[
(7.14) \quad \mathcal{L}(d_T(x_0, \cdot))[v, v] = \frac{-\sqrt{-1} \cosh^2(d_0)}{4} u[q_0] \wedge \overline{D_{x_1}(v)}
\]
\[
+ \frac{-\sqrt{-1} \cosh^2(d_0)}{4} (D_{x_1}(v) \wedge \overline{D_{x_1}(v)} - D_{x_1}(v) \wedge \overline{D_{x_1}(v)})
\]
for \( v \in T_{x_1}, T_{g, m} \). For \( v_1, v_2 \in T_{x_1}, T_{g, m} \), the Hermitian form of the Levi form is represented as
\[
(7.15) \quad \mathcal{L}(d_T(x_0, \cdot))[v_1, v_2] = \frac{-\sqrt{-1} \cosh^2(d_0)}{4} (D_{x_1}(v_1) \wedge \overline{D_{x_1}(v_2)} - D_{x_1}(v_1) \wedge \overline{D_{x_1}(v_2)})
\]
from (7.14).

For \( r > 0 \), we consider the sphere \( S(x_0, r) = \{ x \in T_{g, m} | d_T(x_0, x) = r \} \) of the Teichmüller distance. For \( x_1 \in S(x_0, r) \), we define
\[
H_{x_1}^{1, 0} = H_{x_1}^{1, 0}(S(x_0, r)) = \{ v \in T_{x_1}, T_{g, m} | \partial d_T(x_0, \cdot)[v] = 0 \} = \{ v \in T_{x_1}, T_{g, m} | u[q_0] \wedge \overline{D_{x_1}(v)} = 0 \}.
\]
Proof. From \(\text{[33, Corollary 1.2]}\), the Teichmüller distance function from \(x_0\) to \((7.17)\), we also deduce that the normal vector \(\nu(x_0)\) is perpendicular to \(H_{x_0}\). From Lemma 7.2, the Levi form of \(u\) is plurisubharmonic (see also \[28, Corollary 3\]). Hence the Levi-form of the Teichmüler disk passing \(x_0\) and \(x_1\). From (7.10),

\[
(7.16) \quad D_{x_1}(\nu(x_1)) = 0, \quad \overline{D}_{x_1}(\nu(x_1)) = \frac{1}{\sinh(2\theta)} \nu[q_0].
\]

Proposition 7.1 (CR tangent space). The complex tangent space \(H_{x_1,0}\) is perpendicular to \(\nu(x_1)\) with respect to the Levi form of the Teichmüller distance.

Proof. From (7.15) and (7.16), \(\mathcal{L}(d_T(x_0, \cdot ))|v, \nu(x_1)| = 0\) for \(v \in H_{x_1,0}\).

Lemma 7.2 (Non-negativity on \(H_{x_1,0}\)). For \(v \in H_{x_1,0}\),

\[
\sqrt{-1}(\Re_x(v) \wedge \overline{\Re}_x(v) - D_x(v) \wedge \overline{D}_x(v)) \geq 0
\]

Proof. From \[33\] Corollary 1.2], the Teichmüller distance function \(T_{g,m} \ni x \mapsto d_T(x_0, x)\) is plurisubharmonic (see also \[28, Corollary 3\]). Hence the Levi-form of the distance function is non-negative on \(H_{x_1,0}\). The assertion follows from (7.14).

7.6. Log-tanh of \(d_T\) is plurisubharmonic on \(T_{\infty}\). We set

\[
u_{x_0}(x) = \log \tanh(d_T(x_0, x))
\]

for \(x \in T_{g,m}\). From (2.2),

\[
u_{x_0}(\Xi_{x_0}(q)) = \log \|q\|
\]

for \(q \in U_{Q_{x_0}}\). Recall that \(T_{\infty}\) is the top stratum of the stratification of \(T_{g,m} \setminus \{x_0\}\) which is obtained in Theorem 6.

Theorem 8 (Plurisubharmonicity). \(\nu_{x_0}\) is plurisubharmonic on \(T_{\infty}\).

Proof. Let \(x_1 \in T_{\infty}\) and \(q_0 \in T_{x_0} \setminus \{x_1 = \Xi_{x_0}(q_0)\}\) as above. Since \(\nu_{x_0}(g(\lambda)) = \log \|q_0\|^\lambda\) \((\lambda \in \{\lambda \mid \lambda < \epsilon\}\) from the direct calculation, the Levi form of \(\nu_{x_0}\) is given as

\[
\mathcal{L}(\nu_{x_0})(v, \nu) = \frac{\sqrt{-1}}{4 \tanh(d_0)} \left( \Re_x(v) \wedge \overline{\Re}_x(v) - D_x(v) \wedge \overline{D}_x(v) \right) - \frac{1}{16 \tanh^2(d_0)} \left| \nu[q_0] \wedge \overline{\nu}_x(v) \right|^2
\]

for \(v \in T_{x_1, T_{g,m}}\). From (7.3) and (7.8), (7.14) and (7.16),

\[
\mathcal{L}(\nu_{x_0})(\nu(x_1), \overline{\nu(x_1)}) = \frac{\sqrt{-1}}{4 \tanh(d_0)} \frac{\nu[q_0]}{\sinh(2\theta)} \wedge \frac{\overline{\nu}[q_0]}{\sinh(2\theta)} - \frac{1}{16 \tanh^2(d_0)} \left| \nu[q_0] \wedge \frac{\nu[q_0]}{\sinh(2\theta)} \right|^2 = 0.
\]

From Lemma 7.2, the Levi form of \(\nu_{x_0}\) is non-negative on \(H_{x_1,0}\). Applying the calculation in Proposition (7.1) to (7.17), we also deduce that the normal vector \(\nu(x_1)\) is perpendicular to \(H_{x_1,0}\) with respect to the Levi form of \(\nu_{x_0}\). Therefore, the Levi form of \(\nu_{x_0}\) is non-negative on the whole \(T_{x_1, T_{g,m}}\).
7.7. **Topological description of the Levi form.** The space $\mathcal{MF}$ carries a natural symplectic structure with the Thurston symplectic form $\omega_{Th}$ (cf. [35]). Dumas [9] Theorem 5.3 introduced a Kähler (symplectic) structure on each stratum of $Q_{x_0}$ discussed in [6,1] which defined from the Levi-form of the $L^1$-norm on $Q_{x_0}$, and observed that the Hubbard-Masur homeomorphism (2.3) is a real-analytic symplectomorphism on each stratum of $Q_{x_0}$ (cf. [9] Theorem 5.8). In fact, when $q_0 \in Q_{x_0}$ is generic, Dumas showed that the Hubbard-Masur homeomorphism (2.3) is a diffeomorphism around $q_0$ and satisfies

$$
\omega_{Th}(dV_{x_0}(\psi_1), dV_{x_0}(\psi_2)) = \Im \int_{\mathcal{M}_0} \frac{\psi_1 \psi_2}{4|q_0|} \ d\lambda = \frac{1}{8} \int_{\mathcal{M}_0} \Im \left( \frac{\pi_{q_0}^* \psi_1}{\omega_{q_0}} \right) \wedge \Re \left( \frac{\pi_{q_0}^* \psi_2}{\omega_{q_0}} \right)
$$

for $\psi_1, \psi_2 \in T_{q_0}Q_{x_0} = Q_{x_0}$ (cf. [33] and [9 §5.2]).

**Remark 9.** Dumas [9] discussed the Hubbard-Masur homeomorphism (2.3) by assigning the horizontal foliations to quadratic differentials in accordance with Hubbard and Masur’s original discussion. The original Hubbard-Masur homeomorphism $\mathcal{H}_{x_0}: Q_{x_0} \to \mathcal{MF}$ satisfies $V_{x_0}(g) = \mathcal{H}_{x_0}(-g)$. Hence, $dV_{x_0}(\psi) = -d\mathcal{H}_{x_0}(\psi)$ for $\psi \in Q_{x_0} = T_{q_0}Q_{x_0}$. Thus, the formula (7.18) also holds in our case.

Let us go back to the notion in (7.2) Notice that

$$
\nu_2 \wedge \overline{\nu_2} - \nu_1 \wedge \overline{\nu_1} = (\nu_2 + \overline{\nu_1}) \wedge (\nu_2 + \nu_1) = (\Re(u[q_\lambda])) - (\Re(u[q_\lambda]))
$$

at $\lambda = 0$, where $\lambda = \xi_1 + \xi_2 \sqrt{-1}$. Therefore, when

$$
q_\lambda = \mathbb{Z}_{x_0}(g(\lambda)) = q_0 + \xi_1 \psi_1 + \xi_2 \psi_2 + o(1)
$$

as $\lambda = \xi_1 + \xi_2 \sqrt{-1} \to 0$, from (7.3), (7.8), (7.18) and (7.19),

$$
\mathcal{L}(u_{x_0}[\nu, \overline{\nu}]) = \frac{1}{||q_0||^2} \omega_{Th}(dV_{x_0}(\psi_1), dV_{x_0}(\psi_2)) - \frac{|u[q_0] \wedge \overline{\mathbb{D}_x(\psi)}|^2}{16||q_0||^2},
$$

and

$$
\mathcal{L}(u_{x_0}[\nu, \overline{\nu}]) = 8 \omega_{Th}(dV_{x_0}(q_0), dV_{x_0}(\psi_2 - \sqrt{-1} \psi_1)) + \sqrt{-1} 8 \omega_{Th}(dV_{x_0}(q_0), dV_{x_0}(\psi_1 + \sqrt{-1} \psi_2)).
$$

In particular, when $v \in H^1_{x_1}$ for $x_1 = g(0)$, we conclude

$$
\mathcal{L}(u_{x_0}[\nu, \overline{\nu}]) = \frac{1}{||q_0||^2} \omega_{Th}(dV_{x_0}(\psi_1), dV_{x_0}(\psi_2)).
$$

As a corollary, we deduce

$$
\omega_{Th}(dV_{x_0}(\psi_1), dV_{x_0}(\psi_2)) \geq \frac{|u[q_0] \wedge \overline{\mathbb{D}_x(\psi)}|^2}{16||q_0||^2} \geq 0.
$$

From the definition, $dV_{x_0}(\psi_1) \in T_{\psi(q_0)}\mathcal{MF}$ is the infinitesimal transverse cocycle (in the sense of Bonahon [4]) of the initial differentials $\{q_\lambda\}_\lambda$ associated along the $\xi_i$-direction at $\lambda = 0$. Thus, the non-negativity derived from (7.20) of the Thurston symplectic pairing between the infinitesimal transverse cocycles $dV_{x_0}(\psi_1)$
and $dV_{x_0}(\psi_2)$ is a necessary condition to describe complex-analytic deformations of Teichmüller mappings from the topological aspect in Teichmüller theory.

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