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On Frobenius-destabilized rank-2 vector bundles over curves

Herbert Lange and Christian Pauly

Abstract. Let X be a smooth projective curve of genus $g \geq 2$ over an algebraically closed field k of characteristic $p > 0$. Let \mathcal{M}_X be the moduli space of semistable rank-2 vector bundles over X with trivial determinant. The relative Frobenius map $F: X \rightarrow X_1$ induces by pull-back a rational map $V: \mathcal{M}_{X_1} \dashrightarrow \mathcal{M}_X$. In this paper we show the following results.

- (1) For any line bundle L over X , the rank- p vector bundle F_*L is stable.
- (2) The rational map V has base points, i.e., there exist stable bundles E over X_1 such that F^*E is not semistable.
- (3) Let $\mathcal{B} \subset \mathcal{M}_{X_1}$ denote the scheme-theoretical base locus of V . If $g = 2$, $p > 2$ and X ordinary, then \mathcal{B} is a 0-dimensional local complete intersection of length $\frac{2}{3}p(p^2 - 1)$ and the degree of V equals $\frac{1}{3}p(p^2 + 2)$.

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Introduction

Let X be a smooth projective curve of genus $g \geq 2$ over an algebraically closed field k of characteristic $p > 0$. Denote by $F: X \rightarrow X_1$ the relative k -linear Frobenius map. Here $X_1 = X \times_{k, \sigma} k$, where $\sigma: \text{Spec}(k) \rightarrow \text{Spec}(k)$ is the Frobenius of k (see e.g. [R], Section 4.1). We denote by \mathcal{M}_X , respectively \mathcal{M}_{X_1} , the moduli space of semistable rank-2 vector bundles on X , respectively X_1 , with trivial determinant. The Frobenius F induces by pull-back a rational map (the Verschiebung)

$$V: \mathcal{M}_{X_1} \dashrightarrow \mathcal{M}_X, \quad [E] \mapsto [F^*E].$$

Here $[E]$ denotes the S-equivalence class of the semistable bundle E . It is shown [MS] that V is generically étale, hence separable and dominant, if X or equivalently X_1 is an ordinary curve. Our first result is

Theorem 1. *Over any smooth projective curve X_1 of genus $g \geq 2$ there exist stable rank-2 vector bundles E with trivial determinant, such that F^*E is not semistable. In other words, V has base points.*

Note that this is a statement for an arbitrary curve of genus $g \geq 2$ over k , since associating X_1 to X induces an automorphism of the moduli space of curves of genus g over k . The existence of Frobenius-destabilized bundles was already proved in [LP2], Theorem A.4, by specializing the so-called Gunning bundle on a Mumford-Tate curve. The proof given in this paper is much simpler than the previous one. Given a line bundle L over X , the generalized Nagata–Segre theorem asserts the existence of rank-2 subbundles E of the rank- p bundle F_*L of a certain (maximal) degree. Quite surprisingly, these subbundles E of maximal degree turn out to be stable and Frobenius-destabilized.

In the case $g = 2$ the moduli space \mathcal{M}_X is canonically isomorphic to the projective space \mathbb{P}_k^3 and the set of strictly semistable bundles can be identified with the Kummer surface $\text{Kum}_X \subset \mathbb{P}_k^3$ associated to X . According to [LP2], Proposition A.2, the rational map

$$V: \mathbb{P}_k^3 \dashrightarrow \mathbb{P}_k^3$$

is given by polynomials of degree p , which are explicitly known in the cases $p = 2$ [LP1] and $p = 3$ [LP2]. Let \mathcal{B} be the scheme-theoretical base locus of V , i.e., the subscheme of \mathbb{P}_k^3 determined by the ideal generated by the 4 polynomials of degree p defining V . Clearly its underlying set equals (see [O1], Theorem A.6)

$$\text{supp } \mathcal{B} = \{E \in \mathcal{M}_{X_1} \cong \mathbb{P}_k^3 \mid F^*E \text{ is not semistable}\}$$

and $\text{supp } \mathcal{B} \subset \mathbb{P}_k^3 \setminus \text{Kum}_{X_1}$. Since V has no base points on the ample divisor Kum_{X_1} , we deduce that $\dim \mathcal{B} = 0$. Then we show

Theorem 2. *Assume $p > 2$. Let X_1 be an ordinary curve of genus $g = 2$. Then the 0-dimensional scheme \mathcal{B} is a local complete intersection of length*

$$\frac{2}{3}p(p^2 - 1).$$

Since \mathcal{B} is a local complete intersection, the degree of V equals $\deg V = p^3 - l(\mathcal{B})$ where $l(\mathcal{B})$ denotes the length of \mathcal{B} (see e.g. [O1], Proposition 2.2). Hence we obtain the

Corollary. *Under the assumption of Theorem 2*

$$\deg V = \frac{1}{3}p(p^2 + 2).$$

The underlying idea of the proof of Theorem 2 is rather simple: we observe that a vector bundle $E \in \text{supp } \mathcal{B}$ corresponds via adjunction to a subbundle of the rank- p vector bundle $F_*(\theta^{-1})$ for some theta characteristic θ on X (Proposition 3.1). This is the motivation to introduce Grothendieck's Quot-scheme \mathcal{Q} parametrizing rank-2

subbundles of degree 0 of the vector bundle $F_*(\theta^{-1})$. We prove that the two 0-dimensional schemes \mathcal{B} and \mathcal{Q} decompose as disjoint unions $\coprod \mathcal{B}_\theta$ and $\coprod \mathcal{Q}_\eta$ where θ and η vary over theta characteristics on X and p -torsion points of JX_1 respectively and that \mathcal{B}_θ and \mathcal{Q}_0 are isomorphic, if X is ordinary (Proposition 4.6). In particular since \mathcal{Q} is a local complete intersection, \mathcal{B} also is.

In order to compute the length of \mathcal{B} we show that \mathcal{Q} is isomorphic to a determinantal scheme \mathcal{D} defined intrinsically by the 4-th Fitting ideal of some sheaf. The non-existence of a universal family over the moduli space of rank-2 vector bundles of degree 0 forces us to work over a different parameter space constructed via the Hecke correspondence and carry out the Chern class computations on this parameter space.

The underlying set of points of \mathcal{B} has already been studied in the literature. In fact, using the notion of p -curvature, S. Mochizuki [Mo] describes points of \mathcal{B} as “dormant atoms” and obtains, by degenerating the genus-2 curve X to a singular curve, the above mentioned formula for their number ([Mo], Corollary 3.7, p. 267). Moreover he shows that for a general curve X the scheme \mathcal{B} is reduced. In this context we also mention the recent work of B. Osserman [O1], [O2], which explains the relationship of $\text{supp } \mathcal{B}$ with Mochizuki’s theory.

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1. Stability of the direct image F_*L

Let X be a smooth projective curve of genus $g \geq 2$ over an algebraically closed field of characteristic $p > 0$ and let $F: X \rightarrow X_1$ denote the relative Frobenius map. Let L be a line bundle over X with

$$\deg L = g - 1 + d,$$

for some integer d . Applying the Grothendieck–Riemann–Roch theorem to the morphism F , we obtain

Lemma 1.1. *The slope of the rank- p vector bundle F_*L equals*

$$\mu(F_*L) = g - 1 + \frac{d}{p}.$$

The following result will be used in Section 3.

Proposition 1.2. *If $g \geq 2$, then the vector bundle F_*L is stable for any line bundle L on X .*

Proof. Suppose that the contrary holds, i.e., F_*L is not stable. Consider its Harder–Narasimhan filtration

$$0 = E_0 \subset E_1 \subset E_2 \subset \cdots \subset E_l = F_*L,$$

such that the quotients E_i/E_{i-1} are semistable with $\mu(E_i/E_{i-1}) > \mu(E_{i+1}/E_i)$ for all $i \in \{1, \dots, l-1\}$. If F_*L is not semistable, we denote $E := E_1$. If F_*L is semistable, we denote by E any proper semistable subbundle of the same slope. Then clearly

$$\mu(E) \geq \mu(F_*L). \quad (1)$$

In case $r = \operatorname{rk} E > \frac{p-1}{2}$, we observe that the quotient bundle

$$Q = \begin{cases} F_*L/E_{l-1} & \text{if } F_*L \text{ is not semistable,} \\ F_*L/E & \text{if } F_*L \text{ is semistable,} \end{cases}$$

is also semistable and that its dual Q^* is a subbundle of $(F_*L)^*$. Moreover, by relative duality $(F_*L)^* = F_*(L^{-1} \otimes \omega_X^{\otimes 1-p})$ and by assumption $\operatorname{rk} Q^* \leq p - r \leq \frac{p-1}{2}$. Hence, replacing if necessary E and L by Q^* and $L^{-1} \otimes \omega_X^{\otimes 1-p}$, we may assume that E is semistable and $r \leq \frac{p-1}{2}$.

Now, by [SB], Corollary 2, we have the inequality

$$\mu_{\max}(F^*E) - \mu_{\min}(F^*E) \leq (r-1)(2g-2), \quad (2)$$

where $\mu_{\max}(F^*E)$ (resp. $\mu_{\min}(F^*E)$) denotes the slope of the first (resp. last) graded piece of the Harder–Narasimhan filtration of F^*E . The inclusion $E \subset F_*L$ gives, by adjunction, a nonzero map $F^*E \rightarrow L$. Hence

$$\deg L \geq \mu_{\min}(F^*E) \geq \mu_{\max}(F^*E) - (r-1)(2g-2) \geq p\mu(E) - (r-1)(2g-2).$$

Combining this inequality with (1) and using Lemma 1.1, we obtain

$$g-1 + \frac{d}{p} = \mu(F_*L) \leq \mu(E) \leq \frac{g-1+d}{p} + \frac{(r-1)(2g-2)}{p},$$

which simplifies to

$$(g-1) \leq (g-1) \left(\frac{2r-1}{p} \right).$$

This is a contradiction, since we have assumed $r \leq \frac{p-1}{2}$ and therefore $\frac{2r-1}{p} < 1$. \square

Remark 1.3. We observe that the vector bundles F_*L are destabilized by Frobenius, because of the nonzero canonical map $F^*F_*L \rightarrow L$ and clearly $\mu(F^*F_*L) > \deg L$. For further properties of the bundles F_*L , see [JRXY], Section 5.

Remark 1.4. In the context of Proposition 1.2 we mention the following open question: given a finite separable morphism between smooth curves $f: Y \rightarrow X$ and a line bundle $L \in \text{Pic}(Y)$, is the direct image f_*L stable? For a discussion, see [B2].

2. Existence of Frobenius-destabilized bundles

Let the notation be as in the previous section. We recall the generalized Nagata–Segre theorem, proved by Hirschowitz, which says

Theorem 2.1. *For any vector bundle G of rank r and degree δ over any smooth curve X and for any integer n , $1 \leq n \leq r - 1$, there exists a rank- n subbundle $E \subset G$, satisfying*

$$\mu(E) \geq \mu(G) - \left(\frac{r-n}{r}\right)(g-1) - \frac{\varepsilon}{rn}, \quad (3)$$

where ε is the unique integer with $0 \leq \varepsilon \leq r-1$ and $\varepsilon + n(r-n)(g-1) \equiv n\delta \pmod{r}$.

Remark 2.2. The previous theorem can be deduced (see [L], Remark 3.14) from the main theorem of [Hir] (for its proof, see <http://math.unice.fr/~ah/math/Brill/>).

Proof of Theorem 1. We apply Theorem 2.1 to the rank- p vector bundle F_*L on X_1 and $n = 2$, where L is a line bundle of degree $g-1+d$ on X , with $d \equiv -2g+2 \pmod{p}$: There exists a rank-2 vector bundle $E \subset F_*L$ such that

$$\mu(E) \geq \mu(F_*L) - \frac{p-2}{p}(g-1). \quad (4)$$

Note that our assumption on d was made to have $\varepsilon = 0$.

Now we will check that any E satisfying inequality (4) is stable with F^*E not semistable.

(i) E is stable: Let N be a line subbundle of E . The inclusion $N \subset F_*L$ gives, by adjunction, a nonzero map $F^*N \rightarrow L$, which implies (see also [JRXY], Proposition 3.2 (i))

$$\deg N \leq \mu(F_*L) - \frac{p-1}{p}(g-1).$$

Comparing with (4) we see that $\deg N < \mu(E)$.

(ii) F^*E is not semistable. In fact, we claim that L destabilizes F^*E . For the proof note that Lemma 1.1 implies

$$\mu(F_*L) - \frac{p-2}{p}(g-1) = \frac{2g-2+d}{p} > \frac{g-1+d}{p} = \frac{\deg L}{p} \quad (5)$$

since $g \geq 2$. Together with (4) this gives $\mu(E) > \frac{\deg L}{p}$ and hence

$$\mu(F^*E) > \deg L.$$

This implies the assertion, since by adjunction we obtain a nonzero map $F^*E \rightarrow L$.

Replacing E by a subsheaf of suitable degree, we may assume that inequality (4) is an equality. In that case, because of our assumption on d , $\mu(E)$ is an integer, hence $\deg E$ is even. In order to get trivial determinant, we may tensorize E with a suitable line bundle.

This shows the existence of a stable rank-2 vector bundle E with F^*E not semistable, which is equivalent to the existence of base points of V (see e.g. [O1], Theorem A.6). \square

3. Frobenius-destabilized bundles in genus 2.

From now on we assume that X is an ordinary curve of genus $g = 2$ and the characteristic of k is $p > 2$. Recall that \mathcal{M}_X denotes the moduli space of semistable rank-2 vector bundles with trivial determinant over X and \mathcal{B} the scheme-theoretical base locus of the rational map

$$V: \mathcal{M}_{X_1} \cong \mathbb{P}_k^3 \dashrightarrow \mathbb{P}_k^3 \cong \mathcal{M}_X,$$

which is given by polynomials of degree p .

First of all we will show that the 0-dimensional scheme \mathcal{B} is the disjoint union of subschemes \mathcal{B}_θ indexed by theta characteristics of X .

Proposition 3.1. (a) *Let E be a vector bundle on X_1 such that $E \in \text{supp } \mathcal{B}$. Then we have*

(i) *There exists a unique theta characteristic θ on X such that $\text{Hom}(E, F_*(\theta^{-1})) \neq 0$.*

(ii) *Any rank-2 vector bundle E of degree 0 satisfying $\text{Hom}(E, F_*(\theta^{-1})) \neq 0$ is a subbundle of $F_*(\theta^{-1})$, i.e. the quotient $F_*(\theta^{-1})/E$ is torsion free.*

(b) *Let θ be a theta characteristic on X . Any rank-2 subbundle $E \subset F_*(\theta^{-1})$ of degree 0 has the following properties*

(i) *E is stable and F^*E is not semistable,*

- (ii) $F^*(\det E) = \mathcal{O}_X$,
- (iii) $\dim \operatorname{Hom}(E, F_*(\theta^{-1})) = 1$ and $\dim H^1(E^* \otimes F_*(\theta^{-1})) = 5$,
- (iv) E is a rank-2 subbundle of maximal degree.

Proof. (a) By [LS], Corollary 2.6, we know that, for every $E \in \operatorname{supp} \mathcal{B}$ the bundle F^*E is the nonsplit extension of θ^{-1} by θ , for some theta characteristic θ on X (note that $\operatorname{Ext}^1(\theta^{-1}, \theta) \cong k$). By adjunction we get a nonzero homomorphism $\psi: E \rightarrow F_*(\theta^{-1})$, which shows (i). Uniqueness of θ will be proved below.

As for (ii), we have to show that ψ is of maximal rank. Suppose it is not, then there is a line bundle N on the curve X_1 such that ψ factorizes as $E \rightarrow N \rightarrow F_*(\theta^{-1})$. By stability of E we have $\deg N > 0$. On the other hand, by adjunction, we get a nonzero homomorphism $F^*N \rightarrow \theta^{-1}$ implying $p \cdot \deg N \leq -1$, a contradiction. Hence $\psi: E \rightarrow F_*(\theta^{-1})$ is injective. Moreover E is even a subbundle of $F_*(\theta^{-1})$, since otherwise there exists a subbundle $E' \subset F_*(\theta^{-1})$ with $\deg E' > 0$ and which fits into the exact sequence

$$0 \longrightarrow E \longrightarrow E' \xrightarrow{\pi} T \longrightarrow 0,$$

where T is a torsion sheaf supported on an effective divisor. Varying π , we obtain a family of bundles $\ker \pi \subset E'$ of dimension > 0 and $\det \ker \pi = \mathcal{O}_{X_1}$. This would imply (see proof of Theorem 1) $\dim \mathcal{B} > 0$, a contradiction.

Finally, since θ is the maximal destabilizing line subbundle of F^*E , it is unique.

(b) We observe that inequality (4) holds for the pair $E \subset F_*(\theta^{-1})$. Hence, by the proof of Theorem 1, E is stable and F^*E is not semistable.

Let $\varphi: F^*E \rightarrow \theta^{-1}$ denote the homomorphism adjoint to the inclusion $E \subset F_*(\theta^{-1})$. The homomorphism φ is surjective, since otherwise F^*E would contain a line subbundle of degree > 1 , contradicting [LS], Satz 2.4. Hence we get an exact sequence

$$0 \rightarrow \ker \varphi \rightarrow F^*E \rightarrow \theta^{-1} \rightarrow 0. \quad (6)$$

On the other hand, let N denote a line bundle on X_1 such that $E \otimes N$ has trivial determinant, i.e. $N^{-2} = \det E$. Applying Corollary 2.6 in [LS] to the bundle $F^*(E \otimes N)$ we get an exact sequence

$$0 \rightarrow \tilde{\theta} \otimes F^*N^{-1} \rightarrow F^*E \rightarrow \tilde{\theta}^{-1} \otimes F^*N^{-1} \rightarrow 0,$$

for some theta characteristic $\tilde{\theta}$. By uniqueness of the destabilizing subbundle of maximal degree of F^*E , this exact sequence must coincide with (6) up to a nonzero constant. This implies that $F^*N \otimes \tilde{\theta} = \theta$, hence $(F^*N)^2 = \mathcal{O}_X$. So we obtain that $\mathcal{O}_X = \det(F^*E) = F^*(\det E)$ proving (ii).

By adjunction the equality $\dim \operatorname{Hom}(E, F_*(\theta^{-1})) = \dim \operatorname{Hom}(F^*E, \theta^{-1}) = 1$ holds. Moreover by Riemann–Roch we obtain $\dim H^1(E^* \otimes F_*(\theta^{-1})) = 5$. This proves (iii).

Finally, suppose that there exists a rank-2 subbundle $E' \subset F_*(\theta^{-1})$ with $\deg E' \geq 1$. Then we can consider the kernel $E = \ker \pi$ of a surjective morphism $\pi: E' \rightarrow T$ onto a torsion sheaf with length equal to $\deg E'$. By varying π and after tensoring $\ker \pi$ with a suitable line bundle of degree 0, we construct a family of dimension > 0 of stable rank-2 vector bundles with trivial determinant which are Frobenius-destabilized, contradicting $\dim \mathcal{B} = 0$. This proves (iv). \square

It follows from Proposition 3.1 (a) that the scheme \mathcal{B} decomposes as a disjoint union

$$\mathcal{B} = \bigsqcup_{\theta} \mathcal{B}_{\theta},$$

where θ varies over the set of all theta characteristics of X and

$$\text{supp } \mathcal{B}_{\theta} = \{E \in \text{supp } \mathcal{B} \mid E \subset F_*(\theta^{-1})\}.$$

Tensor product with a 2-torsion point $\alpha \in JX_1[2] \cong JX[2]$ induces an isomorphism of \mathcal{B}_{θ} with $\mathcal{B}_{\theta \otimes \alpha}$ for every theta characteristic θ . We denote by $l(\mathcal{B})$ and $l(\mathcal{B}_{\theta})$ the length of the schemes \mathcal{B} and \mathcal{B}_{θ} . From the preceding we deduce the relations

$$l(\mathcal{B}) = 16 \cdot l(\mathcal{B}_{\theta}) \quad \text{for every theta characteristic } \theta. \quad (7)$$

4. Grothendieck's Quot-scheme

Let θ be a theta characteristic on X . We consider the functor $\underline{\mathcal{Q}}$ from the opposite category of k -schemes of finite type to the category of sets defined by

$$\begin{aligned} \underline{\mathcal{Q}}(S) = \{ & \sigma: \pi_{X_1}^*(F_*(\theta^{-1})) \rightarrow \mathcal{G} \rightarrow 0 \mid \mathcal{G} \text{ coherent over } X_1 \times S, \text{ flat over } S, \\ & \deg \mathcal{G}|_{X_1 \times \{s\}} = \text{rk } \mathcal{G}|_{X_1 \times \{s\}} = p - 2 \text{ for all } s \in S\} / \cong \end{aligned}$$

where $\pi_{X_1}: X_1 \times S \rightarrow X_1$ denotes the natural projection and $\sigma \cong \sigma'$ for quotients σ and σ' if and only if there exists an isomorphism $\lambda: \mathcal{G} \rightarrow \mathcal{G}'$ such that $\sigma' = \lambda \circ \sigma$.

Grothendieck showed in [G] (see also [HL], Section 2.2) that the functor $\underline{\mathcal{Q}}$ is representable by a k -scheme, which we denote by \mathcal{Q} . A k -point of \mathcal{Q} corresponds to a quotient $\sigma: F_*(\theta^{-1}) \rightarrow G$, or equivalently to a rank-2 subsheaf $E = \ker \sigma \subset F_*(\theta^{-1})$ of degree 0 on X_1 . By Proposition 3.1 (a) (ii) any subsheaf E of degree 0 is a subbundle of $F_*(\theta^{-1})$, which implies that any sheaf $\mathcal{G} \in \underline{\mathcal{Q}}(S)$ is locally free (see also [MuSa] or [L], Lemma 3.8). Moreover we note that by Proposition 3.1 (b) (iv) the bundle E has maximal degree as a subbundle of $F_*(\theta^{-1})$.

Hence taking the kernel of σ induces a bijection of $\underline{\mathcal{Q}}(S)$ with the following set, which we also denote by $\underline{\mathcal{Q}}(S)$

$$\begin{aligned} \underline{\mathcal{Q}}(S) = \{ & \mathcal{E} \hookrightarrow \pi_{X_1}^*(F_*(\theta^{-1})) \mid \mathcal{E} \text{ locally free sheaf over } X_1 \times S \text{ of rank 2,} \\ & \pi_{X_1}^*(F_*(\theta^{-1}))/\mathcal{E} \text{ locally free, } \deg \mathcal{E}|_{X_1 \times \{s\}} = 0 \text{ for all } s \in S\} / \cong \end{aligned}$$

By Proposition 3.1 (b) the scheme \mathcal{Q} decomposes as a disjoint union

$$\mathcal{Q} = \coprod_{\eta} \mathcal{Q}_{\eta},$$

where η varies over the p -torsion points $\eta \in JX_1[p]_{\text{red}} = \ker(V: JX_1 \rightarrow JX)$. We also denote by V the Verschiebung of JX_1 , i.e. $V(L) = F^*L$, for $L \in JX_1$. The set-theoretical support of \mathcal{Q}_{η} equals

$$\text{supp } \mathcal{Q}_{\eta} = \{E \in \text{supp } \mathcal{Q} \mid \det E = \eta\}.$$

Because of the projection formula, the tensor product with a p -torsion point $\beta \in JX_1[p]_{\text{red}}$ induces an isomorphism of \mathcal{Q}_{η} with $\mathcal{Q}_{\eta \otimes \beta}$. This implies the relation

$$l(\mathcal{Q}) = p^2 \cdot l(\mathcal{Q}_0), \quad (8)$$

since X_1 is assumed to be ordinary. Moreover, by Proposition 3.1 we have the set-theoretical equality

$$\text{supp } \mathcal{Q}_0 = \text{supp } \mathcal{B}_{\theta}.$$

Proposition 4.1. (a) $\dim \mathcal{Q} = 0$.

(b) *The scheme \mathcal{Q} is a local complete intersection at any k -point $e = (E \subset F_*(\theta^{-1})) \in \mathcal{Q}$.*

Proof. Assertion (a) follows from the preceding remarks and $\dim \mathcal{B} = 0$. By [HL], Proposition 2.2.8, assertion (b) follows from the equality $\dim_{[E]} \mathcal{Q} = 0 = \chi(\underline{\text{Hom}}(E, G))$, where $E = \ker(\sigma: F_*(\theta^{-1}) \rightarrow G)$ and $\underline{\text{Hom}}$ denotes the sheaf of homomorphisms. \square

Let \mathcal{N}_{X_1} denote the moduli space of semistable rank-2 vector bundles of degree 0 over X_1 . We denote by $\mathcal{N}_{X_1}^s$ and $\mathcal{M}_{X_1}^s$ the open subschemes of \mathcal{N}_{X_1} and \mathcal{M}_{X_1} corresponding to stable vector bundles. Recall (see [La1], Theorem 4.1) that $\mathcal{N}_{X_1}^s$ and $\mathcal{M}_{X_1}^s$ universally corepresent the functors (see e.g. [HL], Definition 2.2.1) from the opposite category of k -schemes of finite type to the category of sets defined by

$$\begin{aligned} \underline{\mathcal{N}}_{X_1}^s(S) &= \{\mathcal{E} \text{ locally free sheaf over } X_1 \times S \text{ of rank } 2 \mid \mathcal{E}|_{X_1 \times \{s\}} \text{ stable,} \\ &\quad \deg \mathcal{E}|_{X_1 \times \{s\}} = 0 \text{ for all } s \in S\} / \sim, \end{aligned}$$

$$\begin{aligned} \underline{\mathcal{M}}_{X_1}^s(S) &= \{\mathcal{E} \text{ locally free sheaf over } X_1 \times S \text{ of rank } 2 \mid \mathcal{E}|_{X_1 \times \{s\}} \text{ stable} \\ &\quad \text{for all } s \in S, \det \mathcal{E} = \pi_S^* M \text{ for some line bundle } M \text{ on } S\} / \sim, \end{aligned}$$

where $\pi_S: X_1 \times S \rightarrow S$ denotes the natural projection and $\mathcal{E}' \sim \mathcal{E}$ if and only if there exists a line bundle L on S such that $\mathcal{E}' \cong \mathcal{E} \otimes \pi_S^* L$. We denote by $\langle \mathcal{E} \rangle$ the equivalence class of the vector bundle \mathcal{E} for the relation \sim .

Consider the determinant morphism

$$\det: \mathcal{N}_{X_1} \rightarrow JX_1, \quad [E] \mapsto \det E,$$

and denote by $\det^{-1}(0)$ the scheme-theoretical fibre over the trivial line bundle on X_1 . Since $\mathcal{N}_{X_1}^s$ universally corepresents the functor $\underline{\mathcal{N}}_{X_1}^s$, we have an isomorphism

$$\mathcal{M}_{X_1}^s \cong \mathcal{N}_{X_1}^s \cap \det^{-1}(0).$$

Remark 4.2. If $p > 0$, it is not known whether the canonical morphism $\mathcal{M}_{X_1} \rightarrow \det^{-1}(0)$ is an isomorphism (see e.g. [La2], Section 3).

In the sequel we need the following relative version of Proposition 3.1 (b) (ii). By a k -scheme we always mean a k -scheme of finite type.

Lemma 4.3. *Let S be a connected k -scheme and let \mathcal{E} be a locally free sheaf of rank-2 over $X_1 \times S$ such that $\deg \mathcal{E}|_{X_1 \times \{s\}} = 0$ for all points s of S . Suppose that $\mathrm{Hom}(\mathcal{E}, \pi_{X_1}^*(F_*(\theta^{-1}))) \neq 0$. Then we have the exact sequence*

$$0 \longrightarrow \pi_X^*(\theta) \longrightarrow (F \times \mathrm{id}_S)^*\mathcal{E} \longrightarrow \pi_X^*(\theta^{-1}) \longrightarrow 0.$$

In particular

$$(F \times \mathrm{id}_S)^*(\det \mathcal{E}) = \mathcal{O}_{X_1 \times S}.$$

Proof. First we note that by flat base change for $\pi_{X_1}: X_1 \times S \rightarrow X_1$, we have an isomorphism $\pi_{X_1}^*(F_*(\theta^{-1})) \cong (F \times \mathrm{id}_S)_*(\pi_X^*(\theta^{-1}))$. Hence the nonzero morphism $\mathcal{E} \rightarrow \pi_{X_1}^*(F_*(\theta^{-1}))$ gives via adjunction a nonzero morphism

$$\varphi: (F \times \mathrm{id}_S)^*\mathcal{E} \longrightarrow \pi_X^*(\theta^{-1}).$$

We know by the proof of Proposition 3.1 (b) that the fibre $\varphi_{(x,s)}$ over any closed point $(x, s) \in X \times S$ is a surjective k -linear map. Hence φ is surjective by Nakayama and we have an exact sequence

$$0 \longrightarrow \mathcal{L} \longrightarrow (F \times \mathrm{id}_S)^*\mathcal{E} \longrightarrow \pi_X^*(\theta^{-1}) \longrightarrow 0,$$

with \mathcal{L} locally free sheaf of rank 1. By [K], Section 5, the rank-2 vector bundle $(F \times \mathrm{id}_S)^*\mathcal{E}$ is equipped with a canonical connection

$$\nabla: (F \times \mathrm{id}_S)^*\mathcal{E} \longrightarrow (F \times \mathrm{id}_S)^*\mathcal{E} \otimes \Omega_{X \times S/S}^1.$$

We note that $\Omega_{X \times S/S}^1 = \pi_X^*(\omega_X)$, where ω_X denotes the canonical line bundle of X . The first fundamental form of the connection ∇ is an $\mathcal{O}_{X \times S}$ -linear homomorphism

$$\psi_\nabla: \mathcal{L} \longrightarrow \pi_X^*(\theta^{-1}) \otimes \pi_X^*(\omega_X) = \pi_X^*(\theta).$$

The restriction of ψ_{∇} to the curve $X \times \{s\} \subset X \times S$ for any closed point $s \in S$ is an isomorphism (see e.g. proof of [LS], Corollary 2.6). Hence the fibre of ψ_{∇} is a k -linear isomorphism over any closed point $(x, s) \in X \times S$. We conclude that ψ_{∇} is an isomorphism, by Nakayama's lemma and because \mathcal{L} is a locally free sheaf of rank 1.

We obtain the second assertion of the lemma, since

$$(F \times \text{id}_S)^*(\det \mathcal{E}) = \det(F \times \text{id}_S)^* \mathcal{E} = \mathcal{L} \otimes \pi_X^*(\theta^{-1}) = \mathcal{O}_{X_1 \times S}. \quad \square$$

Proposition 4.4. *We assume X ordinary.*

(a) *The forgetful morphism*

$$i: \mathcal{Q} \hookrightarrow \mathcal{N}_{X_1}^s, \quad e = (E \subset F_*(\theta^{-1})) \mapsto E$$

is a closed embedding.

(b) *The restriction i_0 of i to the subscheme $\mathcal{Q}_0 \subset \mathcal{Q}$ factors through $\mathcal{M}_{X_1}^s$, i.e. there is a closed embedding*

$$i_0: \mathcal{Q}_0 \hookrightarrow \mathcal{M}_{X_1}^s.$$

Proof. (a) Let $e = (E \subset F_*(\theta^{-1}))$ be a k -point of \mathcal{Q} . To show that i is a closed embedding at $e \in \mathcal{Q}$, it is enough to show that the differential $(di)_e: T_e \mathcal{Q} \rightarrow T_{[E]} \mathcal{N}_{X_1}$ is injective – note that \mathcal{Q} is proper. Since the bundle E is stable, the Zariski tangent spaces identify with $\text{Hom}(E, G)$ and $\text{Ext}^1(E, E)$ respectively (see e.g. [HL], Proposition 2.2.7 and Corollary 4.5.2). Moreover, if we apply the functor $\text{Hom}(E, \cdot)$ to the exact sequence associated with $e \in \mathcal{Q}$

$$0 \longrightarrow E \longrightarrow F_*(\theta^{-1}) \longrightarrow G \longrightarrow 0,$$

the coboundary map δ of the long exact sequence

$$\begin{aligned} 0 \longrightarrow \text{Hom}(E, E) &\longrightarrow \text{Hom}(E, F_*(\theta^{-1})) \\ &\longrightarrow \text{Hom}(E, G) \xrightarrow{\delta} \text{Ext}^1(E, E) \longrightarrow \dots \end{aligned}$$

identifies with the differential $(di)_e$. By Proposition 3.1 (b) we obtain that the map $\text{Hom}(E, E) \rightarrow \text{Hom}(E, F_*(\theta^{-1}))$ is an isomorphism. Thus $(di)_e$ is injective.

(b) We consider the composite map

$$\alpha: \mathcal{Q} \xrightarrow{i} \mathcal{N}_{X_1}^s \xrightarrow{\det} JX_1 \xrightarrow{V} JX,$$

where the last map is the isogeny given by the Verschiebung on JX_1 , i.e. $V(L) = F^*L$ for $L \in JX_1$. The morphism α is induced by the natural transformation of functors $\underline{\alpha}: \underline{\mathcal{Q}} \Rightarrow \underline{JX}$, defined by

$$\underline{\mathcal{Q}}(S) \longrightarrow \underline{JX}(S), \quad (\mathcal{E} \hookrightarrow \pi_X^*(F_*(\theta^{-1}))) \mapsto (F \times \text{id}_S)^*(\det \mathcal{E}).$$

Using Lemma 4.3 this immediately implies that α factors through the inclusion of the reduced point $\{\mathcal{O}_X\} \hookrightarrow JX$. Hence the image of \mathcal{Q} under the composite morphism $\det \circ i$ is contained in the kernel of the isogeny V , which is the reduced scheme $JX_1[p]_{\text{red}}$, since we have assumed X ordinary. Taking connected components we see that the image of \mathcal{Q}_0 under $\det \circ i$ is the reduced point $\{\mathcal{O}_{X_1}\} \hookrightarrow JX_1$, which implies that $i_0(\mathcal{Q}_0)$ is contained in $\mathcal{N}_{X_1}^s \cap \det^{-1}(0) \cong \mathcal{M}_{X_1}^s$. \square

In order to compare the two schemes \mathcal{B}_θ and \mathcal{Q}_0 we need the following lemma.

Lemma 4.5. (1) *The closed subscheme $\mathcal{B} \subset \mathcal{M}_{X_1}^s$ corepresents the functor $\underline{\mathcal{B}}$ which associates to a k -scheme S the set*

$$\begin{aligned} \underline{\mathcal{B}}(S) = \{ & \mathcal{E} \text{ locally free sheaf over } X_1 \times S \text{ of rank 2} \mid \mathcal{E}|_{X_1 \times \{s\}} \text{ stable for all } s \in S, \\ & 0 \rightarrow \mathcal{L} \rightarrow (F \times \text{id}_S)^* \mathcal{E} \rightarrow \mathcal{M} \rightarrow 0 \text{ for some locally free sheaves } \mathcal{L}, \mathcal{M} \\ & \text{over } X \times S \text{ of rank 1, } \deg \mathcal{L}|_{X \times \{s\}} = -\deg \mathcal{M}|_{X \times \{s\}} = 1 \text{ for all } s \in S, \\ & \det \mathcal{E} = \pi_S^* M \text{ for some line bundle } M \text{ on } S\} / \sim. \end{aligned}$$

(2) *The closed subscheme $\mathcal{B}_\theta \subset \mathcal{M}_{X_1}^s$ corepresents the subfunctor $\underline{\mathcal{B}}_\theta$ of $\underline{\mathcal{B}}$ defined by $\langle \mathcal{E} \rangle \in \underline{\mathcal{B}}_\theta(S)$ if and only if the set-theoretical image of the classifying morphism of \mathcal{L}*

$$\Phi_{\mathcal{L}}: S \longrightarrow \text{Pic}^1(X), \quad s \longmapsto \mathcal{L}|_{X \times \{s\}},$$

is the point $\theta \in \text{Pic}^1(X)$.

Proof. We denote by \mathfrak{M}_X the algebraic stack parametrizing rank-2 vector bundles with trivial determinant over X . Let \mathfrak{M}_X^{ss} and \mathfrak{M}_X^s denote the open substacks of \mathfrak{M}_X parametrizing semistable and stable bundles. We similarly denote the corresponding stacks of bundles over X_1 . The Shatz stratification [Sh] of \mathfrak{M}_X induced by the degree of the first piece of the Harder–Narasimhan filtration reduces in the case of rank-2 vector bundles to a filtration of the stack \mathfrak{M}_X

$$\mathfrak{M}_X^{ss} \subset \mathfrak{M}_X^{\leq 1} \subset \mathfrak{M}_X^{\leq 2} \subset \cdots \subset \mathfrak{M}_X^{\leq n} \subset \cdots \subset \mathfrak{M}_X$$

by open substacks $\mathfrak{M}_X^{\leq n}$. It follows from the semicontinuity of the Harder–Narasimhan filtration ([Sh], Section 5) that, for every integer n , there is a closed reduced substack \mathfrak{M}_X^n of $\mathfrak{M}_X^{\leq n}$ parametrizing vector bundles having a maximal destabilizing line subbundle of degree n . Note that \mathfrak{M}_X^n is the complement of $\mathfrak{M}_X^{\leq n-1}$ in $\mathfrak{M}_X^{\leq n}$. It can be shown (see e.g. [He], Folgerung 2.1.10) that the stacks \mathfrak{M}_X^n and \mathfrak{M}_X are smooth. Let $\mathfrak{V}: \mathfrak{M}_{X_1} \rightarrow \mathfrak{M}_X$ denote the morphism of stacks induced by pull-back under the Frobenius map $F: X \rightarrow X_1$. It follows from [LS], Corollary 2.6, that the restriction of \mathfrak{V} to the open substack $\mathfrak{M}_{X_1}^{ss}$ determines a morphism of stacks

$$\mathfrak{V}^{ss}: \mathfrak{M}_{X_1}^{ss} \longrightarrow \mathfrak{M}_X^{\leq 1}.$$

We will use the following facts about the stack \mathfrak{M}_X .

- The pull-back of $\mathcal{O}_{\mathbb{P}^3}(1)$ by the natural map $\mathfrak{M}_X^{\leq 1} \rightarrow \mathcal{M}_X \cong \mathbb{P}^3$ extends to a line bundle, which we denote by $\mathcal{O}(1)$, over the moduli stack $\mathfrak{M}_X^{\leq 1}$ and $\text{Pic}(\mathfrak{M}_X^{\leq 1}) = \mathbb{Z} \cdot \mathcal{O}(1)$. Moreover, for any positive integer l , there is a natural isomorphism $H^0(\mathfrak{M}_X^{\leq 1}, \mathcal{O}(l)) \cong H^0(\mathcal{M}_{\mathbb{P}^3}, \mathcal{O}_{\mathbb{P}^3}(l))$ (see [BL], Propositions 8.3 and 8.4).
- The closed substack \mathfrak{M}_X^1 is the base locus of the linear system $|\mathcal{O}(1)|$ over the stack $\mathfrak{M}_X^{\leq 1}$ (see Proposition A).

In order to prove part (1) it will be enough to show that the functor $\underline{\mathcal{B}}$ defined in the lemma coincides with the fibre product functor $\mathcal{B} \times_{\mathcal{M}_{X_1}^s} \underline{\mathcal{M}}_{X_1}^s$ – we recall that $\mathcal{M}_{X_1}^s$ universally corepresents the functor $\underline{\mathcal{M}}_{X_1}^s$.

We now compute the fibre product functor $\mathcal{B} \times_{\mathcal{M}_{X_1}^s} \underline{\mathcal{M}}_{X_1}^s$. Let S be a k -scheme and consider a vector bundle $\mathcal{E} \in \mathfrak{M}_{X_1}^s(S)$. Since the subscheme \mathcal{B} is defined as the base locus of the linear system $V^*|\mathcal{O}_{\mathbb{P}^3}(1)|$, we obtain that $\langle \mathcal{E} \rangle \in [\mathcal{B} \times_{\mathcal{M}_{X_1}^s} \underline{\mathcal{M}}_{X_1}^s](S)$ if and only if \mathcal{E} lies in the base locus of $\mathfrak{V}^{ss*}|\mathcal{O}(1)|$ – here we use the isomorphism $|\mathcal{O}_{\mathbb{P}^3}(1)| \cong |\mathcal{O}(1)|$, or equivalently $\mathfrak{V}^{ss}(\mathcal{E}) := (F \times \text{id}_S)^*\mathcal{E} \in \mathfrak{M}_X^{\leq 1}(S)$ lies in the base locus of $|\mathcal{O}(1)|$, which is the closed substack \mathfrak{M}_X^1 .

We now consider the universal exact sequence defined by the Harder–Narasimhan filtration over \mathfrak{M}_X^1 :

$$0 \rightarrow \mathcal{L} \rightarrow (F \times \text{id}_S)^*\mathcal{E} \rightarrow \mathcal{M} \rightarrow 0,$$

with \mathcal{L}, \mathcal{M} locally free sheaves over $X \times S$ such that $\deg \mathcal{L}|_{X \times \{s\}} = -\deg \mathcal{M}|_{X \times \{s\}} = 1$ for any $s \in S$. This shows that the two sets $[\mathcal{B} \times_{\mathcal{M}_{X_1}^s} \underline{\mathcal{M}}_{X_1}^s](S)$ and $\underline{\mathcal{B}}(S)$ coincide. This proves (1).

As for (2), we add the condition that the family \mathcal{E} is Frobenius-destabilized by the theta-characteristic θ . \square

Remark 4.6. Note that in Lemma 4.5 we do not need to assume X ordinary.

Proposition 4.7. *We assume X ordinary. There is a scheme-theoretical equality*

$$\mathcal{B}_\theta = \mathcal{Q}_0$$

as closed subschemes of \mathcal{M}_{X_1} .

Proof. Since \mathcal{B}_θ and \mathcal{Q}_0 corepresent the two functors $\underline{\mathcal{B}}_\theta$ and $\underline{\mathcal{Q}}_0$ it will be enough to show that there is a canonical bijection between the set $\underline{\mathcal{B}}_\theta(S)$ and $\underline{\mathcal{Q}}_0(S)$ for any k -scheme S . We recall that

$$\begin{aligned} \underline{\mathcal{Q}}_0(S) = \{ \mathcal{E} \hookrightarrow \pi_{X_1}^*(F_*(\theta^{-1})) \mid \mathcal{E} \text{ locally free sheaf over } X_1 \times S \text{ of rank 2,} \\ \pi_X^*(F_*(\theta^{-1}))/\mathcal{E} \text{ locally free, } \det \mathcal{E} \cong \mathcal{O}_{X_1 \times S} \} / \cong \end{aligned}$$

Note that the property $\det \mathcal{E} \cong \mathcal{O}_{X_1 \times S}$ is implied as follows: by Proposition 4.4 (b) we have $\det \mathcal{E} \cong \pi_S^* L$ for some line bundle L over S and by Lemma 4.3 we conclude that $L = \mathcal{O}_S$.

First we show that the natural map $\mathcal{Q}_0(S) \longrightarrow \mathcal{M}_{X_1}^s(S)$ is injective. Suppose that there exist $\mathcal{E}, \mathcal{E}' \in \mathcal{Q}_0(S)$ such that $\langle \mathcal{E} \rangle = \langle \mathcal{E}' \rangle$, i.e. $\mathcal{E}' \cong \mathcal{E} \otimes \pi_S^*(L)$ for some line bundle L on S . Then by Lemma 4.3 we have two inclusions

$$i: \pi_X^*(\theta) \longrightarrow (F \times \text{id}_S)^* \mathcal{E}, \quad i': \pi_X^*(\theta) \otimes \pi_S^*(L^{-1}) \longrightarrow (F \times \text{id}_S)^* \mathcal{E}.$$

Composing with the projection $\sigma: (F \times \text{id}_S)^* \mathcal{E} \rightarrow \pi_X^*(\theta^{-1})$ we see that the composite map $\sigma \circ i'$ is identically zero. Hence the two subbundles $\pi_X^*(\theta)$ and $\pi_X^*(\theta) \otimes \pi_S^*(L^{-1})$ coincide, which implies $\pi_S^*(L) = \mathcal{O}_{X_1 \times S}$.

Therefore the two sets $\mathcal{Q}_0(S)$ and $\mathcal{B}_\theta(S)$ are naturally subsets of $\mathcal{M}_{X_1}^s(S)$.

We now show that $\mathcal{Q}_0(S) \subset \mathcal{B}_\theta(S)$. Consider $\mathcal{E} \in \mathcal{Q}_0(S)$. By Proposition 3.1 (b) the bundle $\mathcal{E}|_{X_1 \times \{s\}}$ is stable for all $s \in S$. By Lemma 4.3 we can take $\mathcal{L} = \pi_X^*(\theta)$ and $\mathcal{M} = \pi_X^*(\theta^{-1})$, so that $\langle \mathcal{E} \rangle \in \mathcal{B}_\theta(S)$.

Hence it remains to show that $\mathcal{B}_\theta(S) \subset \mathcal{Q}_0(S)$. Consider a sheaf \mathcal{E} with $\langle \mathcal{E} \rangle \in \mathcal{B}_\theta(S)$ – see Lemma 4.5 (2). As in the proof of Lemma 4.3 we consider the canonical connection ∇ on $(F \times \text{id}_S)^* \mathcal{E}$. Its first fundamental form is an $\mathcal{O}_{X \times S}$ -linear homomorphism

$$\psi_\nabla: \mathcal{L} \longrightarrow \mathcal{M} \otimes \pi_X^*(\omega_X),$$

which is surjective on closed points $(x, s) \in X \times S$. Hence we can conclude that ψ_∇ is an isomorphism. Moreover taking the determinant, we obtain

$$\mathcal{L} \otimes \mathcal{M} = \det(F \times \text{id}_S)^* \mathcal{E} = \pi_S^* M,$$

for some line bundle M on S . Combining both isomorphisms we deduce that

$$\mathcal{L} \otimes \mathcal{L} = \pi_X^*(\omega_X) \otimes \pi_S^* M.$$

Hence its classifying morphism $\Phi_{\mathcal{L} \otimes \mathcal{L}}: S \longrightarrow \text{Pic}^2(X)$ factorizes through the inclusion of the reduced point $\{\omega_X\} \hookrightarrow \text{Pic}^2(X)$. Moreover the composite map of $\Phi_{\mathcal{L}}$ with the duplication map [2]

$$\Phi_{\mathcal{L} \otimes \mathcal{L}}: S \xrightarrow{\Phi_{\mathcal{L}}} \text{Pic}^1(X) \xrightarrow{[2]} \text{Pic}^2(X)$$

coincides with $\Phi_{\mathcal{L} \otimes \mathcal{L}}$. We deduce that $\Phi_{\mathcal{L}}$ factorizes through the inclusion of the reduced point $\{\theta\} \hookrightarrow \text{Pic}^1(X)$. Note that the fibre $[2]^{-1}(\omega_X)$ is reduced, since $p > 2$. Since $\text{Pic}^1(X)$ is a fine moduli space, there exists a line bundle N over S such that

$$\mathcal{L} = \pi_X^*(\theta) \otimes \pi_S^*(N).$$

We introduce the vector bundle $\mathcal{E}_0 = \mathcal{E} \otimes \pi_S^*(N^{-1})$. Then $\langle \mathcal{E}_0 \rangle = \langle \mathcal{E} \rangle$ and we have an exact sequence

$$0 \longrightarrow \pi_X^*(\theta) \longrightarrow (F \times \text{id}_S)^* \mathcal{E}_0 \xrightarrow{\sigma} \pi_X^*(\theta^{-1}) \longrightarrow 0,$$

since $\pi_S^* M = \pi_S^* N^2$. By adjunction the morphism σ gives a nonzero morphism

$$j: \mathcal{E}_0 \longrightarrow (F \times \text{id}_S)_*(\pi_X^*(\theta^{-1})) \cong \pi_{X_1}^*(F_*(\theta^{-1})).$$

We now show that j is injective. Suppose it is not. Then there exists a subsheaf $\tilde{\mathcal{E}}_0 \subset \pi_{X_1}^*(F_*(\theta^{-1}))$ and a surjective map $\tau: \mathcal{E}_0 \rightarrow \tilde{\mathcal{E}}_0$. Let \mathcal{K} denote the kernel of τ . Again by adjunction we obtain a map $\alpha: (F \times \text{id}_S)^* \tilde{\mathcal{E}}_0 \rightarrow \pi_X^*(\theta^{-1})$ such that the composite map

$$(F \times \text{id}_S)^* \mathcal{E}_0 \xrightarrow{\tau^*} (F \times \text{id}_S)^* \tilde{\mathcal{E}}_0 \xrightarrow{\alpha} \pi_X^*(\theta^{-1})$$

coincides with σ . Here τ^* denotes the map $(F \times \text{id}_S)^* \tau$. Since σ is surjective, α is also surjective. We denote by \mathcal{M} the kernel of α . The induced map $\bar{\tau}: \pi_X^*(\theta) = \ker \sigma \rightarrow \mathcal{M}$ is surjective, because τ^* is surjective. Moreover the first fundamental form of the canonical connection $\tilde{\nabla}$ on $(F \times \text{id}_S)^* \tilde{\mathcal{E}}_0$ induces an $\mathcal{O}_{X \times S}$ -linear homomorphism $\psi_{\tilde{\nabla}}: \mathcal{M} \rightarrow \pi_X^*(\theta)$ and the composite map

$$\psi_{\nabla}: \pi_X^*(\theta) \xrightarrow{\bar{\tau}} \mathcal{M} \xrightarrow{\psi_{\tilde{\nabla}}} \pi_X^*(\theta)$$

coincides with the first fundamental form of ∇ of $(F \times \text{id}_S)^* \mathcal{E}_0$, which is an isomorphism. Therefore $\bar{\tau}$ is an isomorphism too. So τ^* is an isomorphism and $(F \times \text{id}_S)^* \mathcal{K} = 0$. We deduce that $\mathcal{K} = 0$.

In order to show that $\mathcal{E}_0 \in \underline{\mathcal{Q}}_0(S)$, it remains to verify that the quotient sheaf $\pi_{X_1}(F_*(\theta^{-1}))/\mathcal{E}_0$ is flat over S . We recall that flatness implies locally freeness because of maximality of degree. But flatness follows from [HL], Lemma 2.1.4, since the restriction of j to $X_1 \times \{s\}$ is injective for any closed $s \in S$ by Proposition 3.1 (a). \square

Since \mathcal{Q}_0 represents the functor $\underline{\mathcal{Q}}_0$, we obtain the following

Corollary 4.8. *The scheme \mathcal{B}_θ represents the functor $\underline{\mathcal{B}}_\theta$ defined in Lemma 4.5.*

Combining Proposition 4.7 with relations (7) and (8), we obtain

Corollary 4.9. *We have*

$$l(\mathcal{B}) = \frac{16}{p^2} \cdot l(\mathcal{Q}).$$

5. Determinantal subschemes

In this section we introduce a determinantal subscheme $\mathcal{D} \subset \mathcal{N}_{X_1}$, whose length will be computed in the next section. We also show that \mathcal{D} is isomorphic to Grothendieck's Quot-scheme \mathcal{Q} . We first define a determinantal subscheme $\tilde{\mathcal{D}}$ of a variety $JX_1 \times Z$ covering \mathcal{N}_{X_1} and then we show that $\tilde{\mathcal{D}}$ is a \mathbb{P}^1 -fibration over an étale cover of $\mathcal{D} \subset \mathcal{N}_{X_1}$.

Since there does not exist a universal bundle over $X_1 \times \mathcal{M}_{X_1}$, following an idea of Mukai [Mu], we consider the moduli space $\mathcal{M}_{X_1}(x)$ of stable rank-2 vector bundles on X_1 with determinant $\mathcal{O}_{X_1}(x)$ for a fixed point $x \in X_1$. According to [N1] the variety $\mathcal{M}_{X_1}(x)$ is a smooth intersection of two quadrics in \mathbb{P}^5 . Let \mathcal{U} denote a universal bundle on $X_1 \times \mathcal{M}_{X_1}(x)$ and denote

$$\mathcal{U}_x := \mathcal{U}|_{\{x\} \times \mathcal{M}_{X_1}(x)}$$

considered as a rank-2 vector bundle on $\mathcal{M}_{X_1}(x)$. Then the projectivized bundle

$$Z := \mathbb{P}(\mathcal{U}_x)$$

is a \mathbb{P}^1 -bundle over $\mathcal{M}_{X_1}(x)$. The variety Z parametrizes pairs (F_z, l_z) consisting of a stable vector bundle $F_z \in \mathcal{M}_{X_1}(x)$ and a non-trivial linear form $l_z: F_z(x) \rightarrow k_x$ on the fibre of F_z over x defined up to a non-zero constant. Thus to any $z \in Z$ one can associate an exact sequence

$$0 \rightarrow E_z \rightarrow F_z \rightarrow k_x \rightarrow 0$$

uniquely determined up to a multiplicative constant. Clearly E_z is semistable, since F_z is stable, and $\det E_z = \mathcal{O}_{X_1}$. Hence we get a diagram (the so-called Hecke correspondence)

$$\begin{array}{ccc} Z & \xrightarrow{\varphi} & \mathcal{M}_{X_1} \cong \mathbb{P}^3 \\ \pi \downarrow & & \\ \mathcal{M}_{X_1}(x) & & \end{array}$$

with $\varphi(z) = [E_z]$ and $\pi(z) = F_z$. We note that there is an isomorphism $\varphi^{-1}(E) \cong \mathbb{P}^1$ (see e.g. [Mu], (3.7)) and that $\pi(\varphi^{-1}(E)) \subset \mathcal{M}_{X_1}(x) \subset \mathbb{P}^5$ is a conic for any stable $E \in \mathcal{M}_{X_1}^s$ (see e.g. [NR2]). On $X_1 \times Z$ there exists a “universal” bundle, which we denote by \mathcal{V} (see [Mu], (3.8)). It has the property

$$\mathcal{V}|_{X_1 \times \{z\}} \cong E_z, \quad \text{for all } z \in Z.$$

Let \mathcal{L} denote a Poincaré bundle on $X_1 \times JX_1$. By abuse of notation we also denote by \mathcal{V} and \mathcal{L} their pull-backs to $X_1 \times JX_1 \times Z$. We denote by π_{X_1} and q the

canonical projections

$$X_1 \xleftarrow{\pi_{X_1}} X_1 \times JX_1 \times Z \xrightarrow{q} JX_1 \times Z.$$

We consider the map m given by tensor product

$$m: JX_1 \times \mathcal{M}_{X_1} \longrightarrow \mathcal{N}_{X_1}, \quad (L, E) \longmapsto L \otimes E.$$

Note that the restriction of m to the stable locus $m^s: JX_1 \times \mathcal{M}_{X_1}^s \longrightarrow \mathcal{N}_{X_1}^s$ is an étale map of degree 16. We denote by ψ the composite map

$$\psi: JX_1 \times Z \xrightarrow{\text{id}_{JX_1} \times \varphi} JX_1 \times \mathcal{M}_{X_1} \xrightarrow{m} \mathcal{N}_{X_1}, \quad \psi(L, z) = L \otimes E_z.$$

Let $D \in |\omega_{X_1}|$ be a smooth canonical divisor on X_1 . We introduce the following sheaves over $JX_1 \times Z$

$$\mathcal{F}_1 = q_*(\mathcal{L}^* \otimes \mathcal{V}^* \otimes \pi_{X_1}^*(F_*(\theta^{-1}) \otimes \omega_{X_1}))$$

and

$$\mathcal{F}_0 = \bigoplus_{y \in D} (\mathcal{L}^* \otimes \mathcal{V}^*|_{\{y\} \times JX_1 \times Z}) \otimes k^{\oplus p}.$$

The next proposition is an even degree analogue of [LN], Theorem 3.1.

Proposition 5.1. (a) *The sheaves \mathcal{F}_0 and \mathcal{F}_1 are locally free of rank $4p$ and $4p - 4$ respectively and there is an exact sequence*

$$0 \longrightarrow \mathcal{F}_1 \xrightarrow{\gamma} \mathcal{F}_0 \longrightarrow R^1 q_*(\mathcal{L}^* \otimes \mathcal{V}^* \otimes \pi_{X_1}^*(F_*(\theta^{-1}))) \longrightarrow 0.$$

Let $\tilde{\mathcal{D}} \subset JX_1 \times Z$ denote the subscheme defined by the 4-th Fitting ideal of the sheaf $R^1 q_*(\mathcal{L}^* \otimes \mathcal{V}^* \otimes \pi_{X_1}^*(F_*(\theta^{-1})))$. We have set-theoretically

$$\text{supp } \tilde{\mathcal{D}} = \{(L, z) \in JX_1 \times Z \mid \dim \text{Hom}(L \otimes E_z, F_*(\theta^{-1})) = 1\},$$

and $\dim \tilde{\mathcal{D}} = 1$.

(b) *Let δ denote the l -adic ($l \neq p$) cohomology class of $\tilde{\mathcal{D}}$ in $JX_1 \times Z$. Then*

$$\delta = c_5(\mathcal{F}_0 - \mathcal{F}_1) \in H^{10}(JX_1 \times Z, \mathbb{Z}_l).$$

Proof. We consider the canonical exact sequence over $X_1 \times JX_1 \times Z$ associated to the effective divisor $\pi_{X_1}^* D$

$$\begin{aligned} 0 \rightarrow \mathcal{L}^* \otimes \mathcal{V}^* \otimes \pi_{X_1}^* F_*(\theta^{-1}) &\xrightarrow{\otimes D} \mathcal{L}^* \otimes \mathcal{V}^* \otimes \pi_{X_1}^* (F_*(\theta^{-1}) \otimes \omega_{X_1}) \\ &\rightarrow \mathcal{L}^* \otimes \mathcal{V}^*|_{\pi_{X_1}^* D} \otimes k^{\oplus p} \rightarrow 0. \end{aligned}$$

By Proposition 1.2 the rank- p vector bundle $F_*(\theta^{-1})$ is stable and since

$$1 - \frac{2}{p} = \mu(F_*(\theta^{-1})) > \mu(L \otimes E) = 0 \quad \text{for all } (L, E) \in JX_1 \times \mathcal{M}_{X_1},$$

we obtain

$$\dim H^1(L^* \otimes E^* \otimes F_*(\theta^{-1}) \otimes \omega_{X_1}) = \dim \operatorname{Hom}(F_*(\theta^{-1}), L \otimes E) = 0.$$

This implies

$$R^1 q_*(\mathcal{L}^* \otimes \mathcal{V}^* \otimes \pi_{X_1}^*(F_*(\theta^{-1}) \otimes \omega_{X_1})) = 0.$$

By the base change theorems the sheaf \mathcal{F}_1 is locally free. Taking direct images by q (note that $q_*(\mathcal{L}^* \otimes \mathcal{V}^* \otimes \pi_{X_1}^* F_*(\theta^{-1})) = 0$ because it is a torsion sheaf), we obtain the exact sequence

$$0 \longrightarrow \mathcal{F}_1 \xrightarrow{\gamma} \mathcal{F}_0 \longrightarrow R^1 q_*(\mathcal{L}^* \otimes \mathcal{V}^* \otimes \pi_{X_1}^*(F_*(\theta^{-1}))) \longrightarrow 0.$$

with \mathcal{F}_1 and \mathcal{F}_0 as in the statement of the proposition. Note that by Riemann–Roch we have

$$\operatorname{rk} \mathcal{F}_1 = 4p - 4 \quad \text{and} \quad \operatorname{rk} \mathcal{F}_0 = 4p.$$

It follows from the proof of Proposition 3.1 (a) that any nonzero homomorphism $L \otimes E \longrightarrow F_*(\theta^{-1})$ is injective. Moreover by Proposition 3.1 (b) (iii) for any subbundle $L \otimes E \subset F_*(\theta^{-1})$ we have $\dim \operatorname{Hom}(L \otimes E, F_*(\theta^{-1})) = 1$, or equivalently $\dim H^1(L^* \otimes E^* \otimes F_*(\theta^{-1})) = 5$. Using the base change theorems we obtain the following series of equivalences

$$\begin{aligned} (L, z) \in \operatorname{supp} \tilde{\mathcal{D}} &\iff \operatorname{rk} \gamma_{(L, z)} < 4p - 4 = \operatorname{rk} \mathcal{F}_1 \\ &\iff \dim H^1(L^* \otimes E^* \otimes F_*(\theta^{-1})) \geq 5 \\ &\iff \dim \operatorname{Hom}(L \otimes E, F_*(\theta^{-1})) \geq 1 \\ &\iff \dim \operatorname{Hom}(L \otimes E, F_*(\theta^{-1})) = 1. \end{aligned}$$

Finally we clearly have the equality $\operatorname{supp} \psi(\tilde{\mathcal{D}}) = \operatorname{supp} \mathcal{Q}$. Since $\dim \mathcal{Q} = 0$ and since $\varphi^{-1}(E) \cong \mathbb{P}^1$ for E stable, we deduce that $\dim \tilde{\mathcal{D}} = 1$. This proves part (a).

Part (b) follows from Porteous' formula, which says that the fundamental class $\delta \in H^{10}(JX_1 \times Z, \mathbb{Z}_l)$ of the determinantal subscheme $\tilde{\mathcal{D}}$ is given (with the notation of [ACGH], p. 86) by

$$\begin{aligned} \delta &= \Delta_{4p-(4p-5), 4p-4-(4p-5)}(c_t(\mathcal{F}_0 - \mathcal{F}_1)) \\ &= \Delta_{5,1}(c_t(\mathcal{F}_0 - \mathcal{F}_1)) \\ &= c_5(\mathcal{F}_0 - \mathcal{F}_1). \end{aligned}$$

□

Let M be a sheaf over a k -scheme S . We denote by

$$\mathrm{Fitt}_n[M] \subset \mathcal{O}_S$$

the n -th Fitting ideal sheaf of M .

We now define the 0-dimensional subscheme $\mathcal{D} \subset \mathcal{N}_{X_1}^s$, which is supported on $\mathrm{supp} \mathcal{Q}$, by defining a scheme structure \mathcal{D}_E for every $E \in \mathrm{supp} \mathcal{Q}$. Note that

$$\mathcal{D} = \coprod_{E \in \mathrm{supp} \mathcal{Q}} \mathcal{D}_E.$$

Consider a bundle $E \in \mathcal{N}_{X_1}^s$ with $E \in \mathrm{supp} \mathcal{Q}$, i.e.

$$\dim \mathrm{Hom}(E, F_*(\theta^{-1})) \geq 1 \iff \dim H^1(E^* \otimes F_*(\theta^{-1})) \geq 5.$$

The GIT-construction of the moduli space $\mathcal{N}_{X_1}^s$ realizes $\mathcal{N}_{X_1}^s$ as a quotient of an open subset \mathcal{U} of a Quot-scheme by the group $\mathbb{P}\mathrm{GL}(N)$ for some N . It can be shown (see e.g. [La2], Section 3) that \mathcal{U} is a principal $\mathbb{P}\mathrm{GL}(N)$ -bundle for the étale topology over $\mathcal{N}_{X_1}^s$. Hence there exists an étale neighbourhood $\tau: \bar{U} \rightarrow U$ of E over which the $\mathbb{P}\mathrm{GL}(N)$ -bundle is trivial, i.e., admits a section. The universal bundle over the Quot-scheme restricts to a bundle \mathcal{E} over $X_1 \times \bar{U}$. Choose a point $\bar{E} \in \bar{U}$ over E . We denote by $\mathcal{D}_{\bar{E}}$ the connected component supported at \bar{E} of the scheme defined by the Fitting ideal sheaf

$$\mathrm{Fitt}_4[R^1\pi_{\bar{U}*}(\mathcal{E}^* \otimes \pi_{X_1}^* F_*(\theta^{-1}))].$$

Lemma 5.2. *Let $\tau: \bar{U} \rightarrow U$ be an étale map and $y \in \bar{U}$, $x \in U$ such that $\tau(y) = x$. Let $\bar{\Lambda} \subset \bar{U}$ be a 0-dimensional scheme supported at y . Then the restriction of τ to $\bar{\Lambda}$ induces an isomorphism of $\bar{\Lambda}$ with its scheme-theoretical image in $\Delta = \tau(\bar{\Lambda}) \subset U$, i.e.*

$$\tau|_{\bar{\Lambda}}: \bar{\Lambda} \xrightarrow{\sim} \Delta \subset U.$$

Proof. We denote by $A = \mathcal{O}_{\bar{U}, y}$, $B = \mathcal{O}_{U, x}$ the local rings at the points y, x and by $\mathfrak{m}_A, \mathfrak{m}_B$ their maximal ideals. Let $I \subset \mathfrak{m}_A$ denote the ideal defining the scheme $\bar{\Lambda}$. Since $\dim \bar{\Lambda} = 0$ there exists an integer n such that $\mathfrak{m}_A^n \subset I$. The natural map $B \hookrightarrow A \twoheadrightarrow A/I$ factorizes as follows

$$\beta: B \twoheadrightarrow B/\mathfrak{m}_B^n \xrightarrow{\alpha} A/\mathfrak{m}_A^n \twoheadrightarrow A/I.$$

Note that α is an isomorphism, since τ is étale (see e.g. [Mum], Corollary 1 of Theorem III.5.3). This shows that β is surjective, hence $\tau|_{\bar{\Lambda}}$ is an isomorphism. \square

Proposition–Definition 5.3. *For $E \in \text{supp } \mathcal{Q}$ we define \mathcal{D}_E as the scheme-theoretical image $\tau(\mathcal{D}_{\bar{E}}) \subset \mathcal{N}_{X_1}^s$ under the étale map τ . Then the scheme \mathcal{D}_E does not depend on the étale neighbourhood $\tau: \bar{U} \rightarrow U$ of E and the point \bar{E} .*

Proof. Consider for $i = 1, 2$ étale neighbourhoods $\tau_i: \bar{U}_i \rightarrow U$ such that universal bundles \mathcal{E}_i exist over $X_1 \times \bar{U}_i$, and points $\bar{E}_i \in \bar{U}_i$ lying over $E \in U$. Because of Lemma 5.2 it will be enough to show that the schemes $\mathcal{D}_{\bar{E}_1}$ and $\mathcal{D}_{\bar{E}_2}$ are isomorphic.

Consider the fibre product $\bar{U} = \bar{U}_1 \times_U \bar{U}_2$ and the point $\bar{E} = (\bar{E}_1, \bar{E}_2) \in \bar{U}$. The two projections $\pi_i: \bar{U} \rightarrow \bar{U}_i$ for $i = 1, 2$ are étale. Moreover $(\text{id}_{X_1} \times \pi_i)^* \mathcal{E}_i \sim \mathcal{E}$, where \mathcal{E} denotes the universal bundle over $X_1 \times \bar{U}$. Since the formation of the Fitting ideal and taking the higher direct image $R^1 \pi_{\bar{U}*}$ commutes with the flat base changes π_1 and π_2 (see [E], Corollary 20.5), we obtain for $i = 1, 2$

$$\pi_i^{-1} [\text{Fitt}_4(R^1 \pi_{\bar{U}_1*}(\mathcal{E}_i^* \otimes \pi_{X_1}^* F_*(\theta^{-1})))] \cdot \mathcal{O}_{\bar{U}} = \text{Fitt}_4(R^1 \pi_{\bar{U}*}(\mathcal{E}^* \otimes \pi_{X_1}^* F_*(\theta^{-1}))).$$

This shows that the connected components supported at \bar{E} of the fibres $\pi_i^{-1}(\mathcal{D}_{\bar{E}_i})$ equal $\mathcal{D}_{\bar{E}}$. Applying Lemma 5.2 to π_i and $\mathcal{D}_{\bar{E}}$ we obtain isomorphisms $\pi_i: \mathcal{D}_{\bar{E}} \rightarrow \mathcal{D}_{\bar{E}_i}$ and we are done. \square

Lemma 5.4. (a) *Let S be a k -scheme and \mathcal{E} a sheaf over $X_1 \times S$ with $\langle \mathcal{E} \rangle \in \mathcal{N}_{X_1}^s(S)$. We suppose that the set-theoretical image of the classifying morphism of \mathcal{E}*

$$\Phi_{\mathcal{E}}: S \longrightarrow \mathcal{N}_{X_1}^s, \quad s \longmapsto \mathcal{E}|_{X_1 \times \{s\}}$$

is a point. Then there exists an Artinian ring A , a morphism $\varphi: S \longrightarrow \Delta := \text{Spec}(A)$ and a locally free sheaf \mathcal{E}_0 over $X_1 \times \Delta$ such that

- (1) $\mathcal{E} \sim (\text{id}_{X_1} \times \varphi)^* \mathcal{E}_0$
- (2) *the natural map $\mathcal{O}_{\Delta} \longrightarrow \varphi_* \mathcal{O}_S$ is injective.*
- (b) *There exists a universal family \mathcal{E}_0 over $X_1 \times \mathcal{D}$.*

Proof. (a) Since the set-theoretical support of $\text{im } \Phi_{\mathcal{E}}$ is a point $x \in \mathcal{N}_{X_1}^s$, there exists an Artinian ring A such that $\Phi_{\mathcal{E}}$ factorizes through the inclusion $\Delta := \text{Spec}(A) \hookrightarrow \mathcal{N}_{X_1}^s$. As explained above there exists an étale neighbourhood $\tau: \bar{U} \rightarrow U$ of x such that there is a universal bundle $\mathcal{E}^{\text{univ}}$ over $X_1 \times \bar{U}$. Choose $y \in \bar{U}$ such that $\tau(y) = x$ and denote by $\bar{\Lambda} \subset \bar{U}$ the connected component supported at y of the fibre $\tau^{-1}(\Delta)$. By Lemma 5.2 there is an isomorphism $\tau: \bar{\Lambda} \xrightarrow{\sim} \Delta$. Denote by \mathcal{E}_0 the restriction of $\mathcal{E}^{\text{univ}}$ to $X_1 \times \bar{\Lambda} \cong X_1 \times \Delta$. This shows property (1). As for (2), we consider the ideal $I \subset A$ defined by $\tilde{I} = \ker(\mathcal{O}_{\text{Spec}(A)} \rightarrow \varphi_* \mathcal{O}_S)$, where \tilde{I} denotes the associated $\mathcal{O}_{\text{Spec}(A)}$ -module. If $I \neq 0$, we replace A by A/I and we are done.

- (b) We take $\Delta = \mathcal{D}_E$ and $\bar{\Lambda} = \mathcal{D}_{\bar{E}}$ and proceed as in (a). \square

Proposition 5.5. *The subscheme $\mathcal{D} \subset \mathcal{N}_{X_1}^s$ represents the functor $\underline{\mathcal{D}}$ which associates to any k -scheme S the set*

$$\underline{\mathcal{D}}(S) = \{\mathcal{E} \text{ locally free sheaf over } X_1 \times S \text{ of rank 2} \mid \deg \mathcal{E}|_{X_1 \times \{s\}} = 0 \\ \text{for all } s \in S, \text{Fitt}_4[R^1\pi_{S*}(\mathcal{E}^* \otimes \pi_{X_1}^*(F_*(\theta^{-1}))]) = 0\} / \sim.$$

Proof. Consider a sheaf \mathcal{E} over $X_1 \times S$ with $\langle \mathcal{E} \rangle \in \mathcal{N}_{X_1}^s(S)$. Then $\langle \mathcal{E} \rangle$ is an element of $[\mathcal{D} \times_{\mathcal{N}_{X_1}^s} \mathcal{N}_{X_1}^s](S)$ if and only if the classifying map $\Phi_{\mathcal{E}}: S \rightarrow \mathcal{N}_{X_1}^s$ factorizes as $S \xrightarrow{\varphi} \mathcal{D} \subset \mathcal{N}_{X_1}^s$. By Lemma 5.4 (b) there exists a universal family \mathcal{E}_0 over $X_1 \times \mathcal{D}$ and we have $\mathcal{E} \sim (\text{id}_{X_1} \times \varphi)^* \mathcal{E}_0$. Since \mathcal{D} is defined (over an étale cover) by a Fitting ideal and since the formation of the Fitting ideal commutes with any base change, we deduce that $[\mathcal{D} \times_{\mathcal{N}_{X_1}^s} \mathcal{N}_{X_1}^s](S) = \underline{\mathcal{D}}(S)$. Since $\mathcal{N}_{X_1}^s$ universally corepresents the functor $\mathcal{N}_{X_1}^s$, this shows that \mathcal{D} corepresents the functor $\underline{\mathcal{D}}$. The existence of a universal family \mathcal{E}_0 over $X \times \mathcal{D}$ implies that \mathcal{D} represents the functor $\underline{\mathcal{D}}$. \square

Proposition 5.6. *There is a scheme-theoretical equality*

$$\tilde{\mathcal{D}} = \psi^{-1} \mathcal{D}.$$

Proof. In order to show that the subschemes $\tilde{\mathcal{D}}$ and $\psi^{-1} \mathcal{D}$ of $JX_1 \times Z$ coincide, it is enough to show that the two subsets $\text{Mor}(S, \tilde{\mathcal{D}})$ and $\text{Mor}(S, \psi^{-1} \mathcal{D})$ of $\text{Mor}(S, JX_1 \times Z)$ coincide for any k -scheme S . Consider $\Phi \in \text{Mor}(S, JX_1 \times Z)$ and denote $\mathcal{E}_{\Phi} := (\text{id}_{X_1} \times \Phi)^*(\mathcal{L} \otimes \mathcal{V})$. By definition of $\tilde{\mathcal{D}}$ we have $\Phi \in \text{Mor}(S, \tilde{\mathcal{D}})$ if and only if $\text{Fitt}_4[R^1\pi_{S*}(\mathcal{E}_{\Phi}^* \otimes \pi_{X_1}^*(F_*(\theta^{-1}))]) = 0$. On the other hand $\Phi \in \text{Mor}(S, \psi^{-1}(\mathcal{D}))$ if and only if $\psi \circ \Phi \in \text{Mor}(S, \mathcal{D})$. The latter set equals $\underline{\mathcal{D}}(S)$ by Proposition 5.5. Since $(\psi \circ \Phi)^* \mathcal{E}_0 \sim \mathcal{E}_{\Phi}$, we are done. \square

Proposition 5.7. *There is a scheme-theoretical equality*

$$\mathcal{D} = \mathcal{Q}.$$

Proof. We note that $\underline{\mathcal{D}}(S)$ and $\underline{\mathcal{Q}}(S)$ are subsets of $\mathcal{N}_{X_1}^s(S)$ (the injectivity of the map $\underline{\mathcal{Q}}(S) \rightarrow \mathcal{N}_{X_1}^s(S)$ is proved similarly as in the proof of Proposition 4.7). Since \mathcal{D} and \mathcal{Q} corepresent the two functors $\underline{\mathcal{D}}$ and $\underline{\mathcal{Q}}$, it will be enough to show that the set $\underline{\mathcal{D}}(S)$ coincides with $\underline{\mathcal{Q}}(S)$ for any k -scheme S .

We first show that $\underline{\mathcal{D}}(S) \subset \underline{\mathcal{Q}}(S)$. Consider a sheaf \mathcal{E} with $\langle \mathcal{E} \rangle \in \underline{\mathcal{D}}(S)$. For simplicity we denote the sheaf $\mathcal{E}^* \otimes \pi_{X_1}^*(F_*(\theta^{-1}))$ by \mathcal{H} . By [Ha], Theorem 12.11, there is an isomorphism

$$R^1\pi_{S*}\mathcal{H} \otimes k(s) \cong H^1(X_1 \times \{s\}, \mathcal{H}|_{X_1 \times \{s\}}) \quad \text{for all } s \in S.$$

From our assumption $\text{Fitt}_4[R^1\pi_{S*}\mathcal{H}] = 0$, we obtain $\dim H^1(X_1 \times \{s\}, \mathcal{H}|_{X_1 \times \{s\}}) \geq 5$, or equivalently $\dim H^0(X_1 \times \{s\}, \mathcal{H}|_{X_1 \times \{s\}}) \geq 1$, i.e., the vector bundle $\mathcal{E}|_{X_1 \times \{s\}}$

is a subsheaf, hence by Proposition 3.1 (a) (ii) a subbundle, of $F_*(\theta^{-1})$. This implies that the set-theoretical image of the classifying map $\Phi_{\mathcal{E}}$ is contained in $\text{supp } \mathcal{Q}$. Taking connected components of S , we can assume that the image of $\Phi_{\mathcal{E}}$ is a point. Therefore we can apply Lemma 5.4: there exists a locally free sheaf \mathcal{E}_0 over $X_1 \times \Delta$ such that $\mathcal{E} \sim (\text{id}_{X_1} \times \varphi)^* \mathcal{E}_0$. For simplicity we write $\mathcal{H}_0 = \mathcal{E}_0^* \otimes \pi_{X_1}^* (F_*(\theta^{-1}))$. In particular $\mathcal{H} = (\text{id}_{X_1} \times \varphi)^* \mathcal{H}_0$. Since the projection $\pi_{\Delta}: X_1 \times \Delta \rightarrow \Delta$ is of relative dimension 1, taking the higher direct image $R^1 \pi_{\Delta*}$ commutes with the (not necessarily flat) base change $\varphi: S \rightarrow \Delta$ ([Ha], Proposition 12.5), i.e., there is an isomorphism

$$\varphi^* R^1 \pi_{\Delta*} \mathcal{H}_0 \cong R^1 \pi_{S*} \mathcal{H}.$$

Since the formation of Fitting ideals also commutes with any base change (see [E], Corollary 20.5), we obtain

$$\text{Fitt}_4[R^1 \pi_{S*} \mathcal{H}] = \text{Fitt}_4[R^1 \pi_{\Delta*} \mathcal{H}_0] \cdot \mathcal{O}_S.$$

Since $\text{Fitt}_4[R^1 \pi_{S*} \mathcal{H}]$ is equal to 0 and $\mathcal{O}_{\Delta} \rightarrow \varphi_* \mathcal{O}_S$ is injective, we deduce that $\text{Fitt}_4[R^1 \pi_{\Delta*} \mathcal{H}_0] = 0$. Since by Proposition 3.1 (b) (iii) $\dim R^1 \pi_{\Delta*} \mathcal{H}_0 \otimes k(s_0) = 5$ for the closed point $s_0 \in \Delta$, we have $\text{Fitt}_5[R^1 \pi_{\Delta*} \mathcal{H}_0] = \mathcal{O}_{\Delta}$. We deduce by [E], Proposition 20.8, that the sheaf $R^1 \pi_{\Delta*} \mathcal{H}_0$ is a free A -module of rank 5. By [Ha], Theorem 12.11 (b), we deduce that there is an isomorphism

$$\pi_{\Delta*} \mathcal{H}_0 \otimes k(s_0) \cong H^0(X_1 \times s_0, \mathcal{H}|_{X_1 \times \{s_0\}})$$

Again by Proposition 3.1 (b) (iii) we obtain $\dim \pi_{\Delta*} \mathcal{H}_0 \otimes k(s_0) = 1$. In particular the \mathcal{O}_{Δ} -module $\pi_{\Delta*} \mathcal{H}_0$ is not zero and therefore there exists a nonzero global section $i \in H^0(\Delta, \pi_{\Delta*} \mathcal{H}_0) = H^0(X_1 \times \Delta, \mathcal{E}_0^* \otimes \pi_{X_1}^* F_*(\theta^{-1}))$. We pull-back i under the map $\text{id}_{X_1} \times \varphi$ and we obtain a nonzero section

$$j = (\text{id}_{X_1} \times \varphi)^* i \in H^0(X_1 \times S, \mathcal{E}^* \otimes \pi_{X_1}^* F_*(\theta^{-1})).$$

Now we apply Lemma 4.3 and we continue as in the proof of Proposition 4.7. This shows that $\langle \mathcal{E} \rangle \in \underline{\mathcal{Q}}(S)$.

We now show that $\underline{\mathcal{Q}}(S) \subset \underline{\mathcal{D}}(S)$. Consider a sheaf $\mathcal{E} \in \underline{\mathcal{Q}}(S)$. The nonzero global section $j \in H^0(X_1 \times S, \mathcal{H}) = H^0(S, \pi_{S*} \mathcal{H})$ determines by evaluation at a point $s \in S$ an element $\alpha \in \pi_{S*} \mathcal{H} \otimes k(s)$. The image of α under the natural map

$$\varphi^0(s): \pi_{S*} \mathcal{H} \otimes k(s) \longrightarrow H^0(X_1 \times \{s\}, \mathcal{H}|_{X_1 \times \{s\}})$$

coincides with $j|_{X_1 \times \{s\}}$ which is nonzero. Also, as $\dim H^0(X_1 \times \{s\}, \mathcal{H}|_{X_1 \times \{s\}}) = 1$, we obtain that $\varphi^0(s)$ is surjective. Hence by [Ha], Theorem 12.11, the sheaf $R^1 \pi_{S*} \mathcal{H}$ is locally free of rank 5. Again by [E], Proposition 20.8, this is equivalent to $\text{Fitt}_4[R^1 \pi_{S*} \mathcal{H}] = 0$ and $\text{Fitt}_5[R^1 \pi_{S*} \mathcal{H}] = \mathcal{O}_S$ and we are done. \square

6. Chern class computations

In this section we will compute the length of the determinantal subscheme $\mathcal{D} \subset \mathcal{N}_{X_1}$ by evaluating the Chern class $c_5(\mathcal{F}_0 - \mathcal{F}_1)$ – see Proposition 5.1 (b).

Let l be a prime number different from p . We have to recall some properties of the cohomology ring $H^*(X_1 \times JX_1 \times Z, \mathbb{Z}_l)$ (see also [LN]). In the sequel we identify all classes of $H^*(X_1, \mathbb{Z}_l)$, $H^*(JX_1, \mathbb{Z}_l)$ etc. with their preimages in $H^*(X_1 \times JX_1 \times Z, \mathbb{Z}_l)$ under the natural pull-back maps.

Let $\Theta \in H^2(JX_1, \mathbb{Z}_l)$ denote the class of the theta divisor in JX_1 . Let f denote a positive generator of $H^2(X_1, \mathbb{Z}_l)$. The cup product $H^1(X_1, \mathbb{Z}_l) \times H^1(X_1, \mathbb{Z}_l) \rightarrow H^2(X_1, \mathbb{Z}_l) \simeq \mathbb{Z}_l$ gives a symplectic structure on $H^1(X_1, \mathbb{Z}_l)$. Choose a symplectic basis e_1, e_2, e_3, e_4 of $H^1(X_1, \mathbb{Z}_l)$ such that $e_1 e_3 = e_2 e_4 = -f$ and all other products $e_i e_j = 0$. We can then normalize the Poincaré bundle \mathcal{L} on $X_1 \times JX_1$ so that

$$c(\mathcal{L}) = 1 + \xi_1 \quad (9)$$

where $\xi_1 \in H^1(X_1, \mathbb{Z}_l) \otimes H^1(JX_1, \mathbb{Z}_l) \subset H^2(X_1 \times JX_1, \mathbb{Z}_l)$ can be written as

$$\xi_1 = \sum_{i=1}^4 e_i \otimes \varphi_i$$

with $\varphi_i \in H^1(JX_1, \mathbb{Z}_l)$. Moreover, we have by the same reasoning, applying [ACGH], p. 335 and p. 21,

$$\xi_1^2 = -2\Theta f \quad \text{and} \quad \Theta^2[JX_1] = 2. \quad (10)$$

Since the variety $\mathcal{M}_{X_1}(x)$ is a smooth intersection of 2 quadrics in \mathbb{P}^5 , one can work out that the l -adic cohomology groups $H^i(\mathcal{M}_{X_1}(x), \mathbb{Z}_l)$ for $i = 0, \dots, 6$ are (see e.g. [Re], p. 0.19)

$$\mathbb{Z}_l, \quad 0, \quad \mathbb{Z}_l, \quad \mathbb{Z}_l^4, \quad \mathbb{Z}_l, \quad 0, \quad \mathbb{Z}_l.$$

In particular $H^2(\mathcal{M}_{X_1}(x), \mathbb{Z}_l)$ is free of rank 1 and, if α denotes a positive generator of it, then

$$\alpha^3[\mathcal{M}_{X_1}(x)] = 4. \quad (11)$$

According to [N2] p. 338 and applying reduction mod p and a comparison theorem, the Chern classes of the universal bundle \mathcal{U} are of the form

$$c_1(\mathcal{U}) = \alpha + f \quad \text{and} \quad c_2(\mathcal{U}) = \chi + \xi_2 + \alpha f \quad (12)$$

with $\chi \in H^4(\mathcal{M}_{X_1}(x), \mathbb{Z}_l)$ and $\xi_2 \in H^1(X_1, \mathbb{Z}_l) \otimes H^3(\mathcal{M}_{X_1}(x), \mathbb{Z}_l)$. As in [N2] and [KN] we write

$$\beta = \alpha^2 - 4\chi \quad \text{and} \quad \xi_2^2 = \gamma f \quad \text{with } \gamma \in H^6(\mathcal{M}_{X_1}(x), \mathbb{Z}_l). \quad (13)$$

Then the relations of [KN] give

$$\alpha^2 + \beta = 0 \quad \text{and} \quad \alpha^3 + 5\alpha\beta + 4\gamma = 0.$$

Hence $\beta = -\alpha^2$, $\gamma = \alpha^3$. Together with (12) and (13) this gives

$$c_2(\mathcal{U}) = \frac{\alpha^2}{2} + \xi_2 + \alpha f \quad \text{and} \quad \xi_2^2 = \alpha^3 f \quad (14)$$

Define $\Lambda \in H^1(JX_1, \mathbb{Z}_l) \otimes H^3(\mathcal{M}_{X_1}(x), \mathbb{Z}_l)$ by

$$\xi_1 \xi_2 = \Lambda f. \quad (15)$$

Then we have for dimensional reasons and noting that $H^5(\mathcal{M}_{X_1}(x), \mathbb{Z}_l) = 0$, that the following classes are all zero:

$$f^2, \quad \xi_1^3, \quad \alpha^4, \quad \xi_1 f, \quad \xi_2 f, \quad \alpha \xi_2, \quad \alpha \Lambda, \quad \Theta^2 \Lambda, \quad \Theta^3. \quad (16)$$

Finally, Z is the \mathbb{P}^1 -bundle associated to the vector bundle \mathcal{U}_x on $\mathcal{M}_{X_1}(x)$. Let $H \in H^2(Z, \mathbb{Z}_l)$ denote the first Chern class of the tautological line bundle on Z . We have, using the definition of the Chern classes $c_i(\mathcal{U})$ and (11),

$$H^2 = \alpha H - \frac{\alpha^2}{2}, \quad H^4 = 0, \quad \alpha^3 H[Z] = 4 \quad (17)$$

and we get for the “universal” bundle \mathcal{V} ,

$$c_1(\mathcal{V}) = \alpha \quad \text{and} \quad c_2(\mathcal{V}) = \frac{\alpha^2}{2} + \xi_2 + Hf. \quad (18)$$

Lemma 6.1. (a) *The cohomology class $\alpha \cdot c_5(\mathcal{F}_0 - \mathcal{F}_1) \in H^{12}(JX_1 \times Z, \mathbb{Z}_l)$ is a multiple of the class $\alpha^3 H \Theta^2$.*

(b) *The pull-back under the map $\varphi: Z \rightarrow \mathcal{M}_{X_1} \cong \mathbb{P}^3$ of the class of a point is the class $H^3 = \frac{\alpha^2}{2} H - \frac{\alpha^3}{2}$.*

Proof. For part (a) it is enough to note that all other relevant cohomology classes vanish, since $\alpha^4 = 0$ and $\alpha \Lambda = 0$.

As for part (b), it suffices to show that $c_1(\varphi^* \mathcal{O}_{\mathbb{P}^3}(1)) = H$. The line bundle $\mathcal{O}_{\mathbb{P}^3}(1)$ is the inverse of the determinant line bundle [KM] over the moduli space \mathcal{M}_{X_1} . Since the formation of the determinant line bundle commutes with any base change (see [KM]), the pull-back $\varphi^* \mathcal{O}_{\mathbb{P}^3}(1)$ is the inverse of the determinant line bundle associated to the family $\mathcal{V} \otimes \pi_{X_1}^* N$ for any line bundle N of degree 1 over X_1 . Hence the first Chern class of $\varphi^* \mathcal{O}_{\mathbb{P}^3}(1)$ can be computed by the Grothendieck–Riemann–Roch theorem applied to the sheaf $\mathcal{V} \otimes \pi_{X_1}^* N$ over $X_1 \times Z$ and the morphism

$\pi_Z: X_1 \times Z \rightarrow Z$. We have

$$\begin{aligned} ch(\mathcal{V} \otimes \pi_{X_1}^* N) \cdot \pi_{X_1}^* td(X_1) &= (2 + \alpha + (-\xi_2 - Hf) + \text{h.o.t.}) (1 + f)(1 - f) \\ &= 2 + \alpha + (-\xi_2 - Hf) + \text{h.o.t.}, \end{aligned}$$

and therefore G-R-R implies that $c_1(\varphi^* \mathcal{O}_{\mathbb{P}^3}(1)) = H$ – note that $\pi_{Z*}(\xi_2) = 0$. \square

Proposition 6.2. *We have*

$$l(\mathcal{D}) = \frac{1}{24} p^3 (p^2 - 1).$$

Proof. Let λ denote the length of the subscheme $m^{-1}(\mathcal{D}) \subset JX_1 \times \mathcal{M}_{X_1}$. Since the map m^s is étale of degree 16, we obviously have the relation $\lambda = 16 \cdot l(\mathcal{D})$. According to Lemma 6.1 (b) we have in $H^{10}(JX_1 \times Z, \mathbb{Z}_l)$

$$[(\text{id} \times \varphi)^{-1}(pt)] = H^3 \cdot \frac{\Theta^2}{2} = \frac{1}{4} \alpha^2 H \Theta^2 - \frac{1}{4} \alpha^3 \Theta^2,$$

where pt denotes the class of a point in $JX_1 \times \mathcal{M}_{X_1}$. Using Proposition 5.6 we obtain that the class $\delta = c_5(\mathcal{F}_0 - \mathcal{F}_1) \in H^{10}(JX_1 \times Z, \mathbb{Z}_l)$ equals $\lambda \cdot (\frac{1}{4} \alpha^2 H \Theta^2 - \frac{1}{4} \alpha^3 \Theta^2)$. Intersecting with α we obtain with Lemma 6.1 (a) and (16)

$$\alpha \cdot c_5(\mathcal{F}_0 - \mathcal{F}_1) = \frac{\lambda}{4} \alpha^3 H \Theta^2. \quad (19)$$

So we have to compute the class $\alpha \cdot c_5(\mathcal{F}_0 - \mathcal{F}_1)$. By (9) and (10),

$$ch(\mathcal{L}) = 1 + \xi_1 - \Theta f$$

whereas by (14), (16) and (18),

$$ch(\mathcal{V}) = 2 + \alpha + (-\xi_2 - Hf) + \frac{1}{12}(-\alpha^3 - 6\alpha Hf) + \frac{1}{12}(\alpha^3 f - \alpha^2 Hf).$$

Moreover

$$ch(\pi_{X_1}^*(F_*(\theta^{-1}) \otimes \omega_{X_1})) \cdot \pi_{X_1}^* td(X_1) = p + (2p - 2)f.$$

So using (14), (15) and (16),

$$\begin{aligned} ch(\mathcal{V}^* \otimes \mathcal{L}^* \otimes \pi_{X_1}^*(F_*(\theta^{-1}) \otimes \omega_{X_1})) \cdot \pi_{X_1}^* td(X_1) \\ = 2p + [(4p - 4)f - p\alpha - 2p\xi_1] \\ + \left[p\alpha\xi_1 - 2p\Theta f - (2p - 2)\alpha f - p\xi_2 - pHf \right] \\ + \left[\frac{p}{12}\alpha^3 + \frac{p}{2}\alpha Hf + p\Lambda f + p\alpha\Theta f \right] \\ + \left[\frac{3p - 2}{12}\alpha^3 f - \frac{p}{12}\alpha^3 \xi_1 - \frac{p}{12}\alpha^2 Hf \right] + \left[-\frac{p}{12}\alpha^3 \Theta f \right]. \end{aligned}$$

Hence by Grothendieck–Riemann–Roch for the morphism q we get

$$\begin{aligned} ch(\mathcal{F}_1) = 4p - 4 + [-(2p - 2)\alpha - 2p\Theta - pH] + \left[\frac{p}{2}\alpha H + p\Lambda + p\alpha\Theta \right] \\ + \left[\frac{3p - 2}{12}\alpha^3 - \frac{p}{12}\alpha^2 H \right] + \left[-\frac{p}{12}\alpha^3\Theta \right]. \end{aligned}$$

From (10) and (18) we easily obtain

$$ch(\mathcal{F}_0) = 4p - 2p\alpha + \frac{p}{6}\alpha^3.$$

So

$$\begin{aligned} ch(\mathcal{F}_0 - \mathcal{F}_1) = 4 + [2p\Theta - 2\alpha + pH] + \left[-\frac{p}{2}\alpha H - p\Lambda - p\alpha\Theta \right] \\ + \left[-\frac{p + 1}{12}\alpha^3 + \frac{p}{12}\alpha^2 H \right] + \left[\frac{p}{12}\alpha^3\Theta \right]. \end{aligned}$$

Defining $p_n := n! \cdot ch_n(\mathcal{F}_0 - \mathcal{F}_1)$ we have according to Newton's recursive formula ([F] p. 56),

$$c_5(\mathcal{F}_0 - \mathcal{F}_1) = \frac{1}{5} \left(p_5 - \frac{5}{6}p_2p_3 - \frac{5}{4}p_1p_4 + \frac{5}{6}p_1^2p_3 + \frac{5}{8}p_1p_2^2 - \frac{5}{12}p_1^3p_2 + \frac{1}{24}p_1^5 \right)$$

with

$$\begin{aligned} p_1 &= 2p\Theta - 2\alpha + pH, & p_2 &= -p(\alpha H + 2\Lambda + 2\alpha\Theta), \\ p_3 &= \frac{1}{2}(-(p + 1)\alpha^3 + p\alpha^2 H), & p_4 &= 2p\alpha^3\Theta, & p_5 &= 0. \end{aligned}$$

Now an immediate computation using (16) and (17) gives

$$\alpha \cdot c_5(\mathcal{F}_0 - \mathcal{F}_1) = \frac{p^3(p^2 - 1)}{6}\alpha^3 H \Theta^2.$$

We conclude from (19) that $\lambda = \frac{2}{3}p^3(p^2 - 1)$ and we are done. \square

Remark 6.3. If $k = \mathbb{C}$, the number of maximal subbundles of a general vector bundle has recently been computed by Y. Holla by using Gromov–Witten invariants [Ho]. His formula ([Ho], Corollary 4.6) coincides with ours.

7. Proof of Theorem 2

The proof of Theorem 2 is now straightforward. It suffices to combine Corollary 4.9, Proposition 5.7 and Proposition 6.2 to obtain the length $l(\mathcal{B})$.

The fact that \mathcal{B} is a local complete intersection follows from the isomorphism $\mathcal{B}_\theta = \mathcal{Q}_0$ (Proposition 4.6) and Proposition 4.1. \square

8. Questions and remarks

- (1) Is the rank- p vector bundle F_*L very stable, i.e. F_*L has no nilpotent ω_{X_1} -valued endomorphisms, for a general line bundle?
- (2) Is $F_*(\theta^{-1})$ very stable for a general curve X ? Note that very-stability of $F_*(\theta^{-1})$ implies reducedness of \mathcal{B} (see e.g. [LN], Lemma 3.3).
- (3) If $g = 2$, we have shown that for a general stable $E \in \mathcal{M}_X$ the fibre $V^{-1}(E)$ consists of $\frac{1}{3}p(p^2 + 2)$ stable vector bundles $E_1 \in \mathcal{M}_{X_1}$, i.e. bundles E_1 such that $F^*E_1 \cong E$ or equivalently (via adjunction) $E_1 \subset F_*E$. The Quot-scheme parametrizing rank-2 subbundles of degree 0 of the rank- $2p$ vector bundle F_*E has expected dimension 0, contains the fibre $V^{-1}(E)$, but it also has a 1-dimensional component arising from Frobenius-destabilized bundles as follows: for any $M \in \text{Pic}^1(X)$ with $\text{Hom}(M^{-1}, E) \neq 0$ consider a stable degree 0 rank-2 bundle E_1 such that F^*E_1 has a nonzero map to M^{-1} .
- (4) If $p = 3$ the base locus \mathcal{B} consists of 16 reduced points, which correspond to the 16 nodes of the Kummer surface associated to JX (see [LP2], Corollary 6.6). For general p , does the configuration of points determined by \mathcal{B} have some geometric significance?

Appendix on base loci and substack of non-semistable vector bundles.

For lack of a suitable reference, we include a detailed proof of the following fact, which was used in Lemma 4.5. We use the notation of Lemma 4.5.

Proposition A. *Let X be a smooth curve of genus 2. The closed substack \mathfrak{M}_X^1 equals the base locus $\text{Bs}|\mathcal{O}(1)|$ of the linear system $|\mathcal{O}(1)|$ over the moduli stack $\mathfrak{M}_X^{\leq 1}$.*

Proof. Let E be a rank-2 vector bundle with trivial determinant over X . It follows from [R], Proposition 1.6.2, that E is semistable if and only if there exists a line bundle M of degree 1 such that $h^0(X, E \otimes M) = h^1(X, E \otimes M) = 0$. Consider the determinant divisor θ_M associated to M . Then $\theta_M \in |\mathcal{O}(1)|$ and for an S -valued point \mathcal{E} of $\mathfrak{M}_X^{\leq 1}$

$$\text{supp}(\theta_M) = \{s \in S \mid h^0(X, \mathcal{E}_s \otimes M) > 0\}.$$

We know (see e.g. [B1], Proposition 2.5) that the linear system $|\mathcal{O}(1)|$ is linearly generated by the divisors θ_M when M varies in $\text{Pic}^1(X)$. The previous equivalence implies that the open complements of the closed substacks $\text{Bs}|\mathcal{O}(1)|$ and \mathfrak{M}_X^1 coincide. To conclude the proposition it remains to show that the base locus $\text{Bs}|\mathcal{O}(1)|$ is a reduced substack of $\mathfrak{M}_X^{\leq 1}$.

The normal bundle N of the closed substack \mathfrak{M}_X^1 in $\mathfrak{M}_X^{\leq 1}$ can be described as follows (e.g. [He], Behauptung 2.1.12, p. 44 or [VL], exposé 4, Théorème 4, p. 90): let \mathcal{E} denote the universal bundle over $X \times \mathfrak{M}_X$ restricted to $X \times \mathfrak{M}_X^1$. There is a canonical inclusion

$$\mathrm{End}_0(\mathcal{E})^{\mathrm{filt}} \subset \mathrm{End}_0(\mathcal{E}),$$

where $\mathrm{End}_0(\mathcal{E})^{\mathrm{filt}}$ denotes the sheaf of tracefree endomorphisms preserving the Harder–Narasimhan filtration. We denote by $\mathrm{End}'_0(\mathcal{E})$ the quotient. Then the normal bundle N equals $R^1 p_* \mathrm{End}'_0(\mathcal{E})$, where p denotes projection onto \mathfrak{M}_X^1 . In the rank-2 case the universal Harder–Narasimhan filtration over $X \times \mathfrak{M}_X^1$ is of the form

$$0 \longrightarrow \mathcal{L} \longrightarrow \mathcal{E} \longrightarrow \mathcal{L}^{-1} \longrightarrow 0,$$

where \mathcal{L} is a degree 1 line bundle. In that case we have $\mathrm{End}'_0(\mathcal{E}) = \mathrm{Hom}(\mathcal{L}, \mathcal{L}^{-1})$ and therefore $N = R^1 p_* \mathcal{L}^{-2}$.

Consider an S -point $\mathcal{E} \in \mathfrak{M}_X^{\leq 1}(S)$ and $x \in S$ such that the vector bundle $\mathcal{E}_x = E \in \mathfrak{M}_X^1(k)$, i.e., E is destabilized by L of degree 1. Consider a line bundle M of degree 1 and its associated determinant divisor θ_M . Then the divisor θ_M contains the closed substack \mathfrak{M}_X^1 . The Kodaira–Spencer map at the point $x \in S$ associated to \mathcal{E} is a k -linear map

$$\kappa: T_x S \longrightarrow H^1(X, \mathrm{End}_0(E)).$$

Note that we consider bundles with trivial determinant, hence κ takes values in $H^1(X, \mathrm{End}_0(E))$. By [Las], Sections II and III, the linear form on $T_x S$ defining the tangent space $T_x \theta_M$ to the determinant divisor θ_M is the map $\Phi \circ \kappa$, where Φ is given by cup product

$$\Phi: H^1(X, \mathrm{End}_0(E)) \longrightarrow \mathrm{Hom}(H^0(X, E \otimes M), H^1(X, E \otimes M)), \quad e \mapsto \cup e.$$

Using Serre duality we identify $H^1(X, \mathrm{End}_0(E))^*$ with $H^0(X, \mathrm{End}_0(E) \otimes \omega)$ and $H^1(X, E \otimes M)$ with $H^0(X, E \otimes \omega M^{-1})^*$. The dual of Φ equals the symmetrized multiplication map of global sections (note that $\mathrm{End}_0(E) = \mathrm{Sym}^2 E$ and $E = E^*$)

$$\mu: H^0(X, E \otimes M) \otimes H^0(X, E \otimes \omega M^{-1}) \longrightarrow H^0(X, \mathrm{End}_0(E) \otimes \omega).$$

Note that both spaces on the left have dimension equal to 1 for general M and that $H^0(X, E \otimes M) = H^0(X, L \otimes M)$ and $H^0(X, E \otimes \omega M^{-1}) = H^0(X, L \otimes \omega M^{-1})$ for general M . This implies that $\dim \mathrm{im}(\mu) = 1$ and

$$\mathrm{im}(\mu) \subset H^0(X, L^2 \omega) \subset H^0(X, \mathrm{End}_0(E) \otimes \omega).$$

We denote by h a generator of $\mathrm{im}(\mu)$. We obtain that for general M the conormal vector defined by $T_x \theta_M$ is given (up to a scalar) by

$$h \in H^0(X, L^2 \omega) = H^1(X, L^{-2})^* = N_x^*.$$

The corresponding rational map

$$\mathrm{Pic}^1(X) \longrightarrow \mathbb{P}H^0(X, L^2\omega) = \mathbb{P}^2, \quad M \mapsto h,$$

is easily seen to be dominant. In particular its image is non degenerate. This shows that the point E is a reduced point of $\mathrm{Bs}|\mathcal{O}(1)|$, because the linear span of the family of conormal vectors defined by $T_x\theta_M$ when M varies in an open set of $\mathrm{Pic}^1(X)$ equals the full space N_x^* . \square

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